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Teaching Radioactive Decay and Radiometric Dating: An Analog Activity Based on Fluid Dynamics

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ABSTRACT

We present a new laboratory activity for teaching radioactive decay by using hydrodynamic processes as an analog and an evaluation of its efficacy in the classroom. A fluid flowing from an upper beaker into a lower beaker (shampoo in this case) behaves mathematically identically to radioactive decay, mimicking the exponential decay process, dependent on the amount of fluid in the upper beaker (representing the amount of parent isotopes) and the size of the hole in the beaker (representing the decay constant). Students measure the fluid depth with time for several runs with varied conditions, then graph their results, create decay equations, manipulate these equations and use them to "date" another experiment. They then apply their new understanding to make predictions regarding complications involved in the decay process and its use in dating (such as daughter loss). Student quiz performance improved from before to after the activity, indicating improved student learning. Student comments and questions indicated deep understanding and a new curiosity about the process and its application. *© 2012 National Association of Geoscience Teachers*. [DOI: 10.5408/11-220.1]

Key words: radioactive decay, radiometric dating, U-series decay, analogy, geochronology

INTRODUCTION

Understanding the process of radioactive decay and its use in radiometric dating is necessary to understanding foundations of modern science, and it is essential knowledge for educated citizenry concerned about current controversies over evolution, the age of the earth, and the use of radioactive decay as an energy source. It is, therefore, an important concept for students in secondary through graduate level science courses to internalize fully. However, because of its very small scale, mathematical treatment, and general unfamiliarity, the topic is fundamentally difficult for students to grasp (Prather, 2005). Commonly, lectures accompanied by demonstrations are employed to teach this topic, using games with dice, cards, or poker chips (Clinikier, 1980; Kowalski, 1981; McGeachy, 1988), computer simulations (Jesse, 2003), electrical circuitry (Evans, 1974; Wunderlich and Peastrel, 1978), or melting ice (Wise, 1990) to mimic the process of decay and explain the concept of half-life. While these demonstrations might illustrate the randomness and/or exponential nature of decay, demonstrations, by their very nature, challenge student engagement.

We present here a newly developed, hands-on laboratory activity for teaching radioactive decay and radiometric dating, and an evaluation of the activity's effectiveness. In this lesson, hydrodynamic principles and processes serve as an analog for radioactive decay processes. Using analogies in teaching, such as the one employed here, has been shown to be a highly effective strategy (Duit, 1991). The use of analogy makes this lesson particularly effective at instilling an intuitive understanding of this complex, unfamiliar process, and its uses by guiding students as they relate radioactive decay to more familiar, intuitive, and approachable processes of fluid flow. The fundamentals that are learned can be adapted to appropriately address any-level classroom, from elementary through graduate courses. We have found it effective at all levels of university education. In the analogy employed herein, students observe the drainage of fluid from a container with a hole in its base into another container (Fig. 1), and they recognize that this process can be described qualitatively and quantitatively in exactly the same way as decay of radioactive parent isotopes and resulting production of daughter isotopes. This allows students to observe, record, and manipulate the process in a way impossible with real radioactive materials. They can see the exponential decrease of flow from the upper beaker to the lower with time (Fig. 2a), and thus clearly envision the exponential decay of radioactive isotopes and the definition of half-lives (Fig. 2b). Students closely observe, measure, graph, and think about the behavior of the fluid flow and then define the factors that control the process, extract and manipulate the controlling equations, and make predictions regarding changes to the initial conditions. They are then asked to transfer this conceptual understanding to the process of radioactive decay. This connection to familiar concepts and the ability to measure and manipulate the process promotes a deep understanding of the decay process and its use in geochronology.

Theoretical Framework

Teaching with Analogs

New ideas are best constructed by building on previously acquired knowledge or by relating the unfamiliar to the familiar (Duit, 1991; Sibley, 2009). This makes analogies particularly useful in teaching, as we use a concrete or familiar source concept to essentially serve as a picture or metaphor that explains an abstract or unfamiliar target concept (Dupin and Joshua, 1989; Duit, 1991). This is particularly useful for geosciences, where many key concepts and processes are not visible or apparent on the Earth's surface or on human timescales (Jee et al., 2010). Along with

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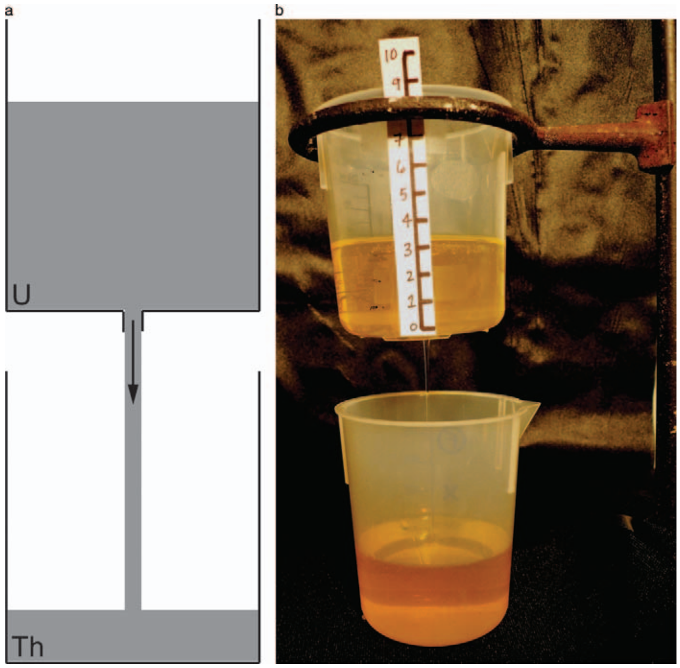

FIGURE 1: (a) Schematic of buckets representing radioactive decay of the parent uranium (fluid in the upper bucket) to the daughter thorium (fluid in the lower bucket), modified from Bourdon et al., 2003. (b) Photo of apparatus set up for radioactive decay lesson.

internalizing the target concept, as science students develop analogical reasoning skills, they are mimicking the reasoning skills used by scientists to create and use models for scientific phenomena (Sibley, 2009). These skills are essential for scientific literacy, and lack of this understanding has been cited as one reason many students struggle with science in general (White and Frederiksen, 1998).

While the use of analogies and analogical models (Jee et al., 2010) in teaching has been shown to enhance student conceptual understanding and build essential scientific reasoning skills, some inherent pitfalls must be avoided in order for the exercise to be effective (Harrison and Treagust, 1993). The source concept or analog must be familiar to the student, corresponding attributes between the source concept and target concept must be explored, unshared attributes between the source concept and target concept must be explicitly discussed, and the instructor must ensure that the students see the source concept in the intended manner (Duit, 1991; Thagard, 1992; Orgill and Bodner, 2006).

In order to prevent these sorts of problems from rendering analogical lessons ineffective, several researchers have developed explicit guidelines for teaching with analogies. We have based our lesson on two of these sets of guidelines that we believe best fit classroom practices and the practicalities of the analog activity we had in mind. Dupin and Joshua (1989) describe guidelines for a "modeling analogy," which we believe applies to our analog well, as it uses a hands-on physical model to relay the source concept (see also Jee et al., 2010). The modeling analogy should have the following five characteristics (Dupin and Joshua, 1989):

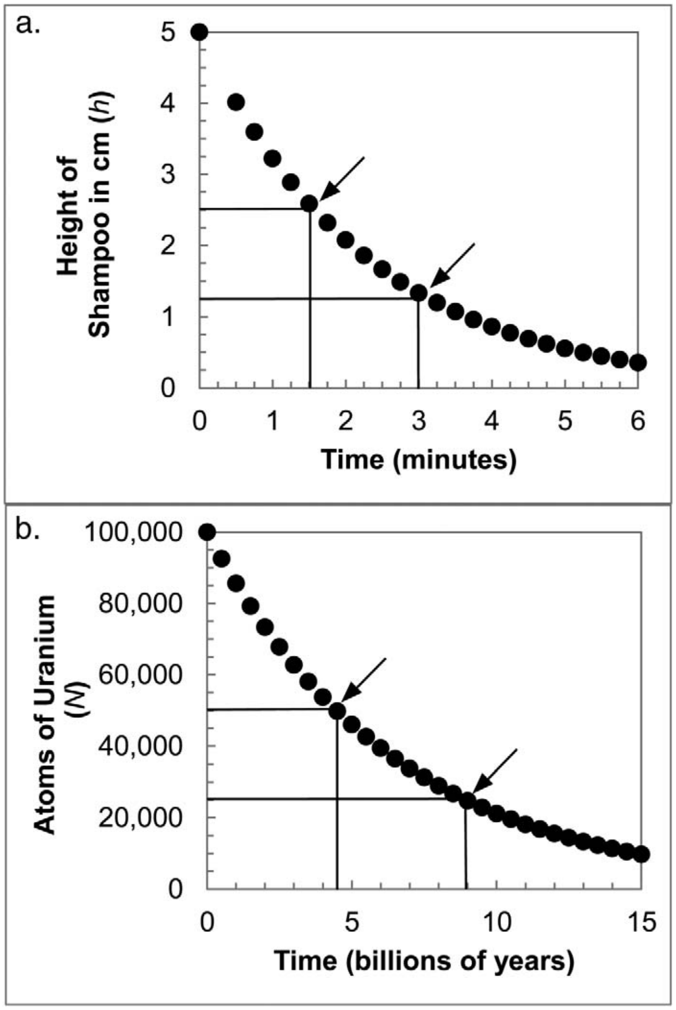

FIGURE 2: (a) Shampoo depth versus time, illustrating exponential nature of the fluid flow. The arrows indicate the apparent half-life of the fluid, 1.5 min. (b) Number of parent atoms (*N*) versus time for ^{238}U by using a decay constant of $1.55 \times 10^{-10} y^{-1}$ (Faure and Mensing, 2005), illustrating exponential nature of decay. The arrows indicate the half-life of ^{238}U, 4.468 billion years (Faure and Mensing, 2005).

1. It serves as a picture or metaphor to put a new concept in concrete form.
2. It must have a "descriptive function" that helps students to understand the target concept and to recognize that the explanation is plausible.
3. It must be less complex than the target concept.
4. It does not have to constitute a real situation. It can be idealized to encourage thorough experiments so that students think deeply about the target concept.
5. The analogical system must have great structural similarity to the target concept, such that it is adaptable to different teaching situations and depths of understanding.

Glynn (1991) proposed the following Teaching with Analogy model, which has proven highly effective (Harrison and Treagust, 1993; see similar instructional supports described in Jee et al., 2010), and on which we based the framework of our lesson:

1. Introduce target concept to be learned.
2. Cue the students' memory of the analogous situation.
3. Identify the relevant features of the analog.
4. Map the similarities between the analog and the target concepts.
5. Identify the comparisons for which the analogy breaks down.
6. Draw conclusions about the target concepts.

Fundamentals: Radioactive Decay

Radioactive decay occurs when an unstable isotope, known as the parent isotope, emits radiation through loss of an ionizing particle from its nucleus. This transforms the isotope into a new, daughter isotope, often a different element. For example, nuclei of ^{238}U are unstable and by emitting alpha particles, decay into ^{234}Th (Faure and Mensing, 2005). While the timing of the loss of a particle from an individual unstable nucleus is random, over long periods and with large numbers of nuclei, the rate of decay is measurable and constant. The decay process can be represented mathematically by the following equation:

$$\frac{dN}{dt} = -\lambda N,$$

where N is the amount of parent isotope, t represents time, and λ is the decay constant for the given isotopic system. Note that the decay rate of parent to daughter is constant for each isotopic system, and is essentially a proportion per unit time. For example, the rate of decay (decay constant) of ^{238}U is 1.55×10^{-10}/yr (Faure and Mensing, 2005). This is an exponential relationship, as shown by Fig. 2b and the solution to the above equation:

$$N(t) = N_0 e^{-\lambda t},$$

where N_0 is the initial amount of parent. Because of the timescales involved and the exponential nature of the process, it is useful to consider decay rates in terms of half-life, or the amount of time it takes for half of the parent material to decay (Fig. 2b). For example, the half-life of ^{238}U is 4.468 billion years (Faure and Mensing, 2005).

In radiometric dating, we measure the amount of parent and daughter isotope in a material and, since the decay rates of radioactive isotopes are known, we can use the above equation to calculate the time that has passed since the product of decay (daughter) began to accumulate. The incorporation of nonradioactively produced daughter isotopes at the formation of the material can occur in natural systems and necessitates careful corrections to obtain accurate results. The loss of daughter isotopes at some time after the formation of the material can also occur, for example, if the material is heated sufficiently, and can be used to determine dates of thermal events that cause the loss.

Fundamentals: A Hydrodynamic Analog for Radioactive Decay

The experiment carried out in this lesson allows students to explore a simple, intuitive hydrodynamic principle in order to develop a qualitative and quantitative understanding of radioactive decay. The experimental analog consists of one beaker with a small hole in the base suspended above another beaker (Fig. 1). Fluid flow from the upper beaker to the lower beaker is controlled by the size of the hole and the hydrostatic pressure being exerted by the column of fluid above. Rate of flow, and thus change in height of fluid in the upper beaker with time, is directly proportional to both the height of fluid in the beaker at any given time and the area of the hole in the bottom of the beaker. This can be stated as:

$$\frac{dh}{dt} = -\alpha h,$$

where h is the height of fluid in the upper beaker, t is time, and α is a flow coefficient that includes the density and viscosity of the fluid, the acceleration because of gravity, the cross-sectional area of the beaker, and the area of the hole. The value is negative because the height of fluid in the upper beaker is decreasing.

Radioactive decay is analogous to the flow of fluid out of the beaker, because the rate of loss of parent isotope is directly proportional to the amount of parent present (the height of fluid) and the decay constant (the flow coefficient α). The equation for radioactive decay is therefore mathematically identical to the equation for fluid flow shown above:

$$\frac{dN}{dt} = -\lambda N,$$

where N is the amount of parent isotope, t is time, and λ is the decay constant for the specific isotope, and the value is negative because the amount of parent is decreasing. When solved, these two equations remain mathematically identical and illustrate the exponential nature of each:

$$h(t) = h_0 e^{-\alpha t}$$

$$N(t) = N_0 e^{-\lambda t},$$

where the subscript 0 indicates the initial condition. This mathematically identical behavior of the two phenomena allows us to use fluid flow as an analog for radioactive decay (Fig. 2). For example, varying the initial height of fluid in the experiment will cause the system to behave similarly to varying the amount of initial parent material in a radioactively decaying system. Varying the area of the hole or the viscosity of the fluid changes the flow coefficient (α), which is analogous to dealing with different isotopic systems that have different decay constants (λ); a larger hole will result in loss of more fluid in a given time, just as a larger decay constant will result in more decay in a given time.

For purposes of the experiment, it is simplest and most intuitive to consider the area of the hole as the determining factor for the decay constant of the draining fluid, because it is easy to see and measure the area of the hole and to create holes with different areas. It would be difficult and less intuitive to try to quantify fluid viscosities, and it is simplest to use the same fluid with the same viscosity throughout the experiment.

Methods

Student Population

We implemented this study in all sections of Dynamic Earth 111 in the Department of Earth and Environmental

Sciences at Vanderbilt University, the laboratory component of the department's introductory geology course (Dynamic Earth 101). Each of the six laboratory sections has 20 students or less, and Dynamic Earth 101 is a co-requisite for the laboratory section. Seventy-six students participated in this study during the second iteration (for which results are reported herein). The students range from freshmen to seniors (18 to 22 yr), and are primarily taking the course to fulfill general education requirements for a laboratory science course, although anyone interested in majoring the in Earth and Environmental Sciences also begins with these two courses, resulting in a wide variety of skill, experience, and interest levels in each laboratory section.

Framework for Educational Study

The concept of radioactive decay and radiometric dating presents an opportunity to address four of the six learning objectives of our introductory geology course, and as such is an ideal topic for this effort to improve student learning. Students who complete this course should be able to: (1) explain the fundamental processes that affect the earth, how these processes are manifested, and why it is important to understand these processes; (2) explain deep time and how it affects the human perspective, particularly their own; (3) evaluate social/political controversies that are based on geological problems as presented in the literature for nonspecialists and assess the scientific validity of arguments presented by each side; and (4) evaluate the importance of scientific uncertainty in understanding the earth's processes and what this means for the future.

This study was performed during two consecutive semesters, with a similar format, but with slight changes in the activity and the assessment during the second semester intended to improve the learning experience and the validity and reliability of the assessment tools. Materials and data reported herein are from the second iteration of the study. Students first attended a lecture on the topic of radioactive decay and radiometric dating. The next week, they were asked to complete a pretest at the beginning of their laboratory session, complete an analog activity during the laboratory period, and take a posttest (identical to the pretest) after completion of the activity (all supplemental material including the pre-/post test and the student laboratory handout is available at: http://dx.doi.org/10.5408/11-220.s1).

The pre-/posttest covered basic concepts, involved some critical thinking, and requested a statement of confidence (numbered 1 through 10) in the student's understanding of the topic. This assessment instrument was developed by the first author, an experienced teaching assistant in this course and a geochronologist, and was revised by the second author, who was highly experienced with both the content and with teaching the relevant concepts in college classrooms. The pre-/posttest was approved by the instructor of Dynamic Earth 101, with more than 30 yr of experience teaching this course and this topic. Attention was paid to Bloom's taxonomy of educational objectives (Anderson and Krathwohl, 2001) in an attempt to assess various degrees of student learning, with questions ranging from knowledge (the lowest level) to create (the highest). During the first iteration of this study, implementation of this instrument elucidated unclear questions that reduced its validity as an assessment tool, so these questions were revised for clarity in the second iteration (for which results are reported herein). The final version was also reviewed and approved by an assistant director of the Vanderbilt University Center for Teaching, a specialist in teaching science and math in higher education.

After the pretest, students completed the analog activity in groups of three to five (see below for full description of the activity; the student handout is available in the supplemental material). They discussed the laboratory assignment in their groups, answering some discussion questions related to the activity that range from basic knowledge to higher-order thinking, including evaluation and prediction/creation (Anderson and Krathwohl, 2001). They ended the laboratory session approximately 2.5 h after taking the pretest by completing a posttest identical to the pretest.

The results from these assessments were tallied and then evaluated and analyzed for statistical significance to determine the impact of the activity and to identify remaining points of confusion and misconceptions. As names were not collected on the pretest, paired data was not available and we therefore report before and after totals for correct responses on the quizzes (Table I), and before and after mean confidence (Table II).

LESSON PLAN

The Student Handout with Instructions, Material Lists, and Follow-up Questions is Available in the Supplemental Material

The analog activity employed four beakers of the same size (we used 250 ml), two of which had a hole in the base and vertical depth scales on the side (in centimeter increments) (Fig. 1b). We used plastic beakers and a drill to form the holes; the exact size of the holes does not matter as long as one is larger than the other is (approximately double in size worked well for us). Each group also used a beaker stand, modeling clay formed into a stopper for the holes, baby shampoo (fill one beaker), a stopwatch, a spatula, and access to Office Excel (Microsoft, Redmond, WA). We chose shampoo as our fluid for ease in cleanup. For the sizes of holes that we used, we found that the discharge rate using baby shampoo (a function of its viscosity) was particularly appropriate, resulting in changes in depth that were readily measurable during the time available for the laboratory activity.

The supplemental material for the student handout has instructions for completing the following activities and for follow-up questions to guide synthesis of the ideas. The activity takes approximately 90 min.

Students positioned the beaker with the smaller hole above a beaker with a solid base by using the beaker stand (Fig. 1). Students plugged the hole with clay and poured a predetermined amount (depth in centimeters) of shampoo into the upper beaker. For their first run, this was 5 cm. They were told that for the experiment, the shampoo in the upper beaker represents the parent isotope, and the flow through the hole represents the decay of the parent to produce the daughter isotope (shampoo in the lower beaker). When they were ready to begin the experiment, they unplugged the hole and allowed the shampoo to flow into the lower beaker (Fig. 1) for a predetermined amount of time (at least 6 min, depending on the viscosity of the shampoo), measuring the liquid depth every 30 s and recording it in the tables on the

TABLE I: Significance test results of correct responses on pre- and posttests. The *z*-test was used to compare the proportions of correct answers on the pre- and posttests for each question and to determine whether the gains were significant at a 1% level.

Question	Pretest Proportion Correct (p_1)	Posttest Proportion Correct (p_2)	Sample Proportion/Mean (p)	SE	z-Score	$P(Z \leq z)$ one-tail	Is gain statistically significant?
1	0.93	0.96	0.95	0.036	−0.73	0.23	No
2	0.54	0.88	0.71	0.074	−4.65	1.30×10^{-6}	Yes
3	0.70	0.95	0.82	0.062	−4.03	3.17×10^{-5}	Yes
4	0.79	0.97	0.88	0.052	−3.51	2.33×10^{-4}	Yes
5	0.13	0.55	0.34	0.054	−7.74	3.19×10^{-14}	Yes

handout (see the supplemental material). Students performed three runs of the experiment: run 1 with the smaller hole and 5 cm of shampoo, run 2 with the smaller hole and 10 cm of shampoo, and run 3 with the larger hole and 5 cm of shampoo. Before each run, students cleaned out the beakers with the spatula, emptying all the shampoo back into its original beaker before starting a new run.

Variation in the initial amount of shampoo mimicked variation in initial amounts of parent material that result in different amounts of decay, although the proportion of material decayed in a given time remained uniform. For example, students could identify the half-life (the length of time until half of the liquid had been lost from the upper beaker) and see that it was the same regardless of how much shampoo there was at the start. The effect of variation in the area of the hole illustrated how variations in decay constant specific to different parent isotopes yield different rates of destruction of parent and production of daughter. The instructor asked students throughout the experiment what observations they were making regarding the process, and discussed what they were seeing and how it related to real radioactive decay, particularly to the concept of half-life.

It is important for the instructor to clarify points of the experiment that are not identical to the target concept. In the case of the shampoo, it is not possible to measure the amount of daughter product accurately for comparison with amount of parent (as we do with isotopes), because as the shampoo flows into the lower beaker, it increases in volume because of the incorporation of bubbles. It is also important to make sure that the students understand that decay does not "slow down" like the fluid velocity. Rather, the decay rate is a constant proportion, but as there is less material to decay, the amount of decay decreases. We discussed these issues in conversations with individual groups as they completed the activity. It is also important to test the viscosity of the fluid chosen before each use, as the properties (primarily the viscosity) might change from semester to semester and therefore could affect the results of the experiment. Viscosity tends to increase as shampoo dehydrates over time; if so, the experiment still works well, but the fluid will flow more slowly and take longer to show appropriate results.

After they completed the experiment runs, questions on the handout guided the students to relate this process to radioactive decay and asked them to name the three factors that controlled the amount of "decay" that had occurred: the amount of shampoo in the upper beaker (parent), the size of the hole (decay constant), and the time. Students then input their recorded data into Office Excel in a format matching the tables they completed in their laboratory handout (see the supplemental material). They then created scatter charts with depth on the *y*-axis and time on the *x*-axis by highlighting these columns and then selecting **Insert Chart** and choosing **x-y Scatter** or **Scatter with only Markers** (Fig. 2a). They **Selected the Series** on the graph and **Added a Trendline**, selecting the **Exponential** type and clicking the box to **Display Equation on Chart**. If the **Exponential** option is not made available by Office Excel when trying to add a trendline to the data, then the data are not exponential, and the experiment was not successful. This only occurred in cases where students somehow disturbed the experiment in mid-run (spilling, for example) and then

TABLE II: Student confidence in understanding of radioactive decay and radiometric dating, self-reported on pre- and posttests.

Confidence Rating[1]	No. of Responses on Pretest	No. of Responses on Posttest	Gain
1	3	0	−3
2	7	1	−6
3	5	1	−4
4	7	2	−5
5	18	3	−15
6	14	6	−8
7	16	13	−3
8	4	28	+26
9	2	10	+8
10	0	11	+11
Mean confidence	5.21	7.72	+48.2%

[1] 1 represents lowest confidence and 10 the highest confidence.

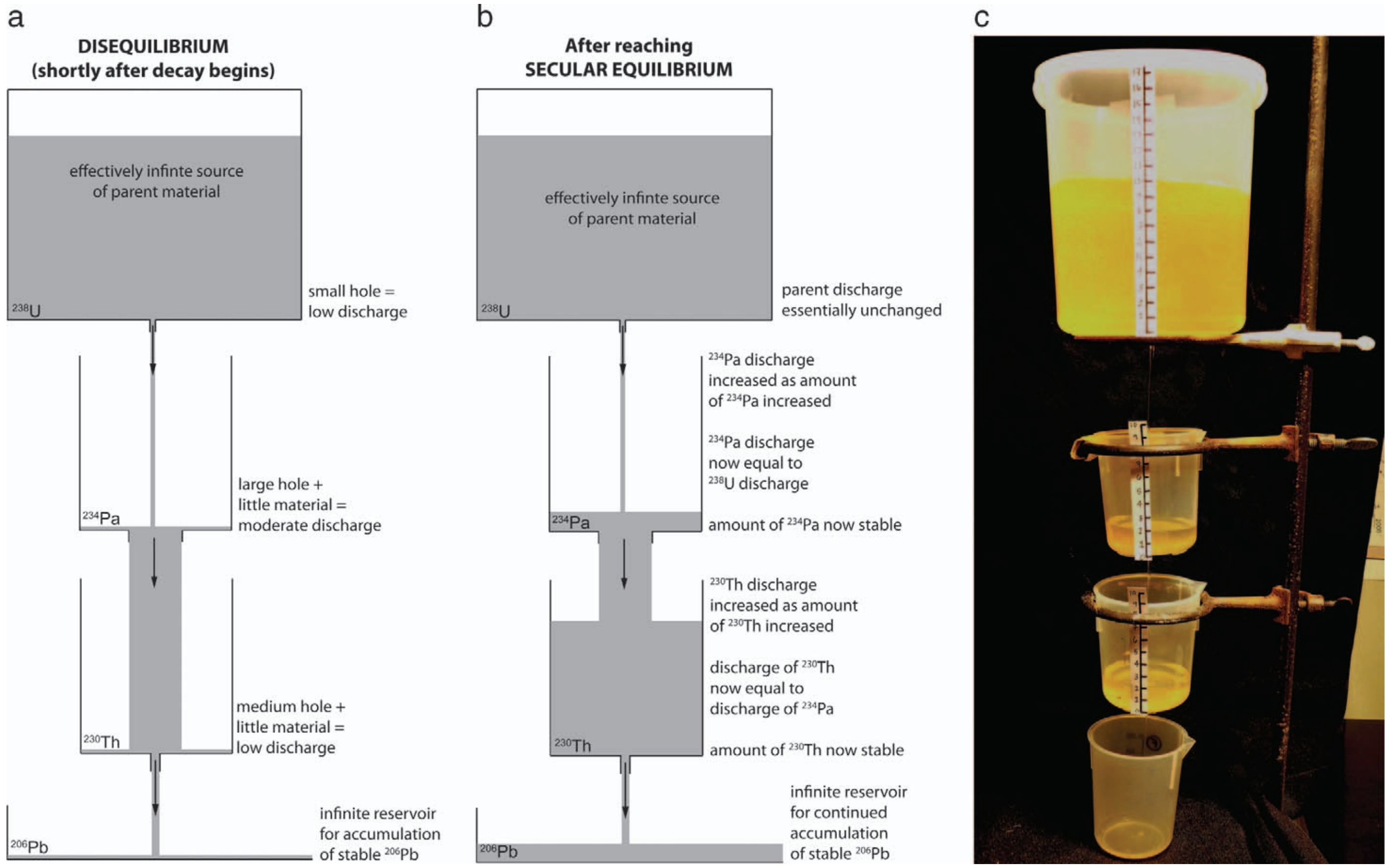

FIGURE 3: (a) Schematic illustrating U-series decay as a set of buckets, with the system out of secular equilibrium, modified from Bourdon et al., 2003. (b) Schematic illustrating U-series decay as a set of buckets, with the system in secular equilibrium, modified from Bourdon et al., 2003. (c) Photo of apparatus set up for U-series decay lesson.

continued collecting data. This was repeated for each run, resulting in three graphs and three equations.

The students then dissected these equations, answering questions on the handout that required them to define what each number represented (see the supplemental material), and concluding that the numbers in the equation that described their data represented the three factors that they had identified as controlling parent loss and daughter gain—the amount of initial parent, the decay constant, and the time—thus describing the decay process. They were asked to rearrange the equation to solve for time, so that it could be used in finding the age of something. As this mathematical manipulation proved to be frustrating to many students, the instructor provided guidance with the math according to the students' individual needs.

For the final step of the activity, each group began a run of the experiment with the small hole and 5 cm of shampoo, like run 1. However, rather than letting it run to completion as before, they plugged the hole at some time of their choosing. They wrote the time on a card and placed it face down beside their experiment. Each group then switched tables, measured the depth of shampoo in the upper beaker, and used the decay equation they had created from their own run 1 to "date" the other group's experiment. They checked their result with the time on the card left by the other group.

After the completion of the activity, the groups were asked discussion questions designed to encourage further thought, including predicting the behavior of the system in various scenarios that were more complex than their experiments (such as the presence of initial parent or the loss of daughter product). They were asked to provide suggestions for how to deal with these issues when trying to use radioactive isotopes for dating.

Lesson Plan Variations for Advanced Students (U-series Disequilibria)

The activity described in this paper was inspired by attempts to explain uranium-series disequilibria dating to advanced students (and geoscientists more senior). Uranium-series disequilibria dating is founded on the fact that uranium decays to form a series of radioactive daughter products that eventually decay to produce lead, the stable daughter product (Fig. 3a, 3b). When decay of uranium begins in a natural substance and there is none of these intermediate products in the material, or they are present in the "wrong" proportions, the system is in disequilibrium (Fig. 3a). As decay progresses and the amount of each intermediate radioactive isotope builds up, the system eventually reaches secular equilibrium, where the amount of decay of the parent (known as the activity) and production of the daughter matches the amount of decay of the daughter (its activity), and the amount of each intermediate isotope no longer changes with time (Fig. 3b). This equilibrium state is reached when

$$\lambda_P N_P = \lambda_{ID} N_{ID},$$

where λ is the decay constant, N is the number of atoms, and the P and ID indicate parent and intermediate daughter, respectively. By measuring the degree of disequilibrium, we can determine the amount of time that has passed since the material was formed and decay began: the farther from equilibrium, the younger; the closer to equilibrium, the older. Once the system effectively reaches secular equilibrium (ratios of isotopes are within analytical uncertainty of matching the equation above), the relative amounts of each isotope remain constant; it is impossible to determine the amount of time that has passed and the intermediate U-series isotopes are no longer useful in dating.

To teach the U-series decay process and disequilibria dating, we use a similar apparatus and the same principles as the basic lesson described previously, but with multiple beakers with variously sized holes suspended in a column (Fig. 3c). The uppermost beaker should have the largest hole, but otherwise, the relative sizes of these holes do not matter, as long as they are significantly different. The top beaker represents the initial parent and should contain a sufficiently large amount of fluid that the flow does not slow down significantly during the experiment. The bottom beaker represents the final, stable daughter product, with beakers in between representing the intermediate, unstable daughter/parent products in the decay process. The flow of shampoo from any given upper beaker to lower beaker behaves identically to the previously described experiment, controlled by the size of the hole and the pressure exerted by the column of fluid. In this case, however, the experimenter can initiate the experiment in disequilibrium (“wrong” levels of shampoo—empty intermediate beakers is easiest) and observe it as it approaches equilibrium. After some time passes, if the mass of shampoo in the uppermost beaker (“U”) is large enough that the level does not change much during the experiment, the entire system reaches equilibrium, where the amount being added from above to each intermediate beaker in the series is identical to the amount being lost out its base. Thus, the heights of fluid in the intermediate beakers stabilize at a level that is inversely proportional to the area of the hole in its base (its decay constant), mimicking the U-series system reaching secular equilibrium. If one chooses to assign specific elements to specific beakers, using appropriate relative sizes of holes (larger holes for elements with larger decay constants, and vice versa) will ensure the appropriateness of the analog.

RESULTS

Statistical Methods and Results

The results of the pre- and posttests were analyzed with a two-proportion z-test, rather than a paired t-test, which is commonly used to compare pre- and posttest data. We selected the two-proportion z-test because we did not collect paired data, which is required for accurate application of the paired t-test. While the group was the same before and after and therefore could be assumed to be related, we felt that falsely pairing the data would provide less accurate statistical results than using the z-test, which assumes random, unassociated groups. The z-test should provide the most conservative statistical results, and we therefore chose this method under the assumption that an indication of significance from this test would be more robust than from a paired t-test with randomly paired data sets.

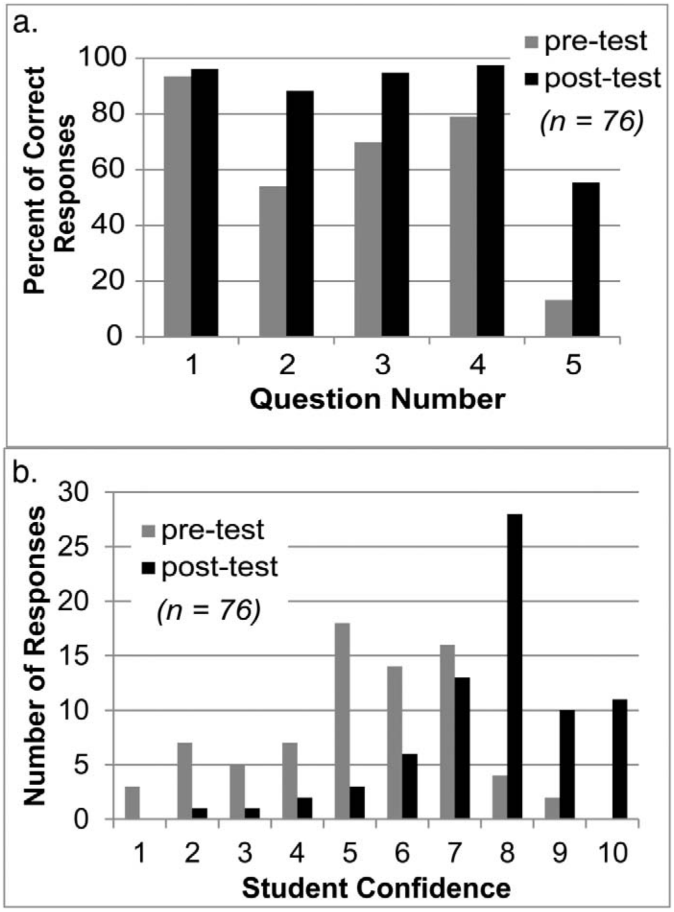

FIGURE 4: (a) Student performance on the pretest versus posttest reported as number of correct responses. (b) Self-reported student confidence on the pretest versus posttest.

The proportion of correct responses was higher for all five questions on the posttest, and was significantly higher at 1% level of significance for questions 2 through 5 (Fig. 4a and Table I). We assume there was little gain in correct responses to question 1 because of its very basic level; most students answered this question correctly on both tests, and there was little room for improvement. The lower number questions on the quiz covered concepts that are more basic, and the higher number questions involved higher level, critical thinking (see the supplemental material). Student gains reflect increased understanding from the pretest to the posttest, ranging from basic knowledge through critical thinking and application, supporting the effectiveness of the activity in improving student learning.

Question 5 specifically required students to take their understanding of the decay process and think critically to determine possible sources of error or inconsistencies that exist in nature. For this question, most of the students who answered incorrectly tended to reproduce statements that were the conclusion of their experiment, rather than think

TABLE III: Student comments and questions and aspect of target concept addressed.

Student Comment/Question	Aspect of Target Concept Addressed
(1) "It slows down as it goes, so as there is less parent material, there is less decay, right?"	Exponential nature of decay
(2) "So, is the decay constant like a proportion of the amount of parent that's there?"	Decay constant, half-life, exponential nature of decay
(3) "If the decay constant depends on what the parent material is, does that mean different parent materials decay at different rates, like different kinds of liquids would go through at different speeds?"	Controls on the rate of decay of a given material
(4) "When it's running out of shampoo, it drips kind of sporadically. Would radioactive decay do the same thing?"	The random nature of decay that is invisible until the very end of the decay process
(5) "If we didn't know the amount of parent we'd started with, could we just measure the amount of parent and the amount of daughter and figure out how long it had been going?"	Radiometric dating in natural materials
(6) "Will it make a difference if there's still some shampoo in the lower beaker when we start?"	Radiometric dating – corrections for presence of initial daughter
(7) "We calculated 2 min 17 s, and they had recorded 2 min 39 ss! It didn't work!"	Uncertainty and error and what meaningful results can look like

about the problem with which they were presented. Adding some variations to the experiment that deal with inconsistencies and wording the question more carefully might lead to better student success with these specific ideas.

Students were asked to rate their confidence in their understanding of the concepts of radioactive decay and radiometric dating, on a scale of 1 to 10 (see the supplemental material). A 48.2% gain in mean confidence of the group suggests overall improved student confidence in their own understanding from pre- to posttest (Table II). The number of students reporting confidence scores of 1 through 7 decreased (for each numerical rating), while the number of students reporting confidence ratings of 8, 9 and 10 increased. These gains suggest that the laboratory activity helped instill a more intuitive understanding of the target concept, thereby improving student confidence in their understanding, further supporting the activity's effectiveness.

Other Evidence of Student Learning

The first test of student success was the formative assessment involving students dating one another's experiments with the equations they had created from their own experiments. This was largely successful, and gave students a meaningful understanding of how radiometric dating works along with confidence in their understanding of the decay process. In the cases where the students were not at first successful with their calculations, it provided an opportunity for them to review their work and their understanding, find mistakes or misconceptions, and correct those errors themselves before trying again and finding success.

In addition to the assessment results that indicate improvement in understanding, the students' comments and questions during the laboratory indicated they were thinking deeply about the process involved and were making new connections between the process itself and its products (Table III). They were clearly able to transfer the concepts illustrated by the analog fluid experiment to the process of radioactive decay and dating, and they seemed to enjoy teasing out the details that were either the same or different in the analog experiment and the original concept. These comments and questions demonstrated the learning that was occurring; for example, student comment no. 5 in Table III showed that the student understood the process of decay well enough to work out on his own how one could use radioactive isotopes to determine the age of a natural material when the amount of initial parent was unknown. These student comments and questions also created opportunities for teaching the higher-order concepts and the more complex details of the process and its uses to students who had become genuinely curious. For example, comment no. 7 (Table III) allowed us to discuss sources of uncertainty and error (in this case including the measuring methods and improperly cleaned beakers) and whether this was still a meaningful result to the experiment or not.

The pretest, as part of this educational study and not an integral part of the course requirements, was voluntary and anonymous. While all students took the pretest, not every test was completed, and it is likely that less effort was expended than on the graded posttest, which is a part of the laboratory structure each week. These student attitudes may affect results. Gains discussed below from pre- to posttest performance could also be affected by test familiarity, since the pre- and posttests were identical and by attendance versus non-attendance of the prelaboratory lecture, which we did not track. It is also reasonable to assume that any intervention or further instruction on the topic could have resulted in some gains in student understanding.

CONCLUSION

Teaching with analogs enhances student understanding of difficult, non-intuitive, unfamiliar concepts by relating them to more intuitive, familiar concepts, if the analog is sufficiently similar to the target concept. Rate of loss of a beaker fluid from a hole in its base (a process that is intuitive to students) is mathematically identical to the process by which radioactive isotopes decay. The laboratory activity described herein allows students to take advantage of the structural similarities of these two processes by studying and manipulating familiar and easily understood hydrodynamic principles and processes, and relating them to the less accessible principles and processes of radioactive decay. This activity instills in students an understanding much deeper, more intuitive of the concepts involved in radioactive decay and radiometric dating than lectures and demonstrations can achieve, resulting in their ability to make predictions regarding complications to the process and to apply this understanding to radiometric dating activities. The results of this study illustrate the effectiveness of this analog activity as a powerful teaching tool for an important, but very difficult and often misunderstood, concept integral to many basic sciences. Along with improved conceptual understanding, the activity provides observational and mathematical confidence to students, with the potential to carry over into other challenges and enhance their confidence and success across disciplines and outside of academia.

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REFERENCES

Anderson, L.W., and Krathwohl, D.R. 2001. A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives. New York: Addison Wesley Longman. p. 352.

Bourdon, B., Turner, S., Henderson, G.M., and Lundstrom, C.C. 2003. Introduction to U-Series geochemistry. *In* Bourdon, B., Henderson, G.M., Lundstrom, C.C., and Turner, S.P., eds., Reviews in mineralogy and geochemistry: Uranium-series geochemistry. Washington DC: The Mineralogical Society. p. 1–21.

Clinikier, L.M. 1980. Teaching principles of radioactive dating and population growth without calculus. *American Journal of Physics*, 48:211–213.

Duit, R. 1991. On the role of analogies and metaphors in learning science. *Science Education*, 75:649–672.

Dupin, J.J., and Joshua, S. 1989. Analogies and "modeling analogies" in teaching: some examples in basic electricity. *Science Education*, 73:207–224.

Evans, G.R. 1974. Radioactive decay chains – an electronic analogue. *Physics Education*, 9:487–489.

Faure, G., and Mensing, T.M. 2005. Isotopes: Principles and applications, 3rd ed. New Jersey: John Wiley & Sons. p. 897.

Glynn, S.M. 1991. Explaining science concepts: A teaching-with-analogies model. *In* Glynn, S., Yeany, R., and Britton, B., eds., The psychology of learning science. New Jersey: Erlbaum, p. 219–240.

Harrison, A.G., and Treagust, D.F. 1993. Teaching with analogies: A case study in grade-10 optics. *Journal of Research in Science Teaching*, 30:1291–1307.

Jee, B.D., Uttal, D.H., Gentner, D., Manduca, C., Shipley, T.F., Tikoff, B., Ormand, C.J., and Sageman, B. 2010. Commentary: Analogical thinking in geoscience education. *Journal of Geoscience Education*, 58:2–13.

Jesse, K.E. 2003. Computer simulation of radioactive decay. *The Physics Teacher*, 41:542–543.

Kowalski, L. 1981. Simulating radioactive decay with dice. *The Physics Teacher*, 19:113.

McGeachy, F. 1988. Radioactive decay – an analog. *The Physics Teacher*, 26:28–29.

Orgill, M.K., and Bodnar, G.M. 2006. An analysis of the effectiveness of analogy used in college-level biochemistry textbooks. *Journal of Research in Science Teaching*, 43:1040–1060.

Prather, E. 2005. Students' beliefs about the role of atoms in radioactive decay and half-life. *Journal of Geoscience Education*, 53:345–354.

Sibley, D.F. 2009. A cognitive framework for reasoning with scientific models. *Journal of Geoscience Education*, 57:255–263.

Thagard, P. 1992. Analogy, explanation, and education. *Journal of Research in Science Teaching*, 29:537–544.

White, B.Y., and Frederiksen, J.R. 1998. Inquiry, modeling and metacognition. *Cognition and Instruction*, 16:3–118.

Wise, D.U. 1990. Using melting ice to teach radiometric dating. *Journal of Geological Education*, 38:38–40.

Wunderlich, F.J., and Peastrel, M. 1978. Electronic analog of radioactive decay. *American Journal of Physics*, 46:189–190.