Supplementary Information

Inquiry into Radioactivity Course Materials - IiR

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http://www.camse.org/radiation

The Inquiry into Radioactivity (IiR) course materials promote the development of radiation literacy among non-science-oriented college or high school students.

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Any opinions, findings, and conclusions or recommendations expressed in these materials are those of the author and do not necessarily reflect the views of the National Science Foundation.

Why teach radiation?

Ionizing radiation and radioactivity is an intriguing topic to teach because it is infrequently taught. Radiation is intrinsically interdisciplinary - the IiR materials make contact with physics, statistics, biology, and chemistry and can be used to introduce atomic structure or certain ideas in probability and statistics. They might help with reviewing certain aspects of cell biology. Ernest Rutherford used alpha radiation to discover that atoms have massive but tiny, charged central nuclei, so in fact the planetary model of the atom was only possible after the discovery of radiation.

Just as importantly, students are very interested in radiation because they know so little about it, even though they have all heard about it. It's great fun to teach a topic that is new to most of your students, and you can be assured that many of your students will be curious.

The topic of radiation deserves more space in our educational system. It was not a very relevant topic until modern society started using radioactive materials and x-rays, but as these uses increase, it becomes increasingly important that more people understand radiation and radioactivity. Currently, very few understand radiation at all.

Research basis

The IiR materials are based on repeated classroom trials and modifications. A number of research projects have uncovered particular learning difficulties and informed improvements to the materials. Papers and posters are available at http://www.camse.org/radiation - look under Research.

Identifications of student thinking were made using two data sources - conceptual evaluations and student work. We have created two conceptual evaluations - one on the general properties of radiation and the other on the structure and properties of atoms. Subscores from these conceptual evaluations used pre or post instruction were sometimes used as indicators of how students were thinking.

The major basis for inferences, however, was a compilation of homework and exam responses. Certain homework and exam questions were selected for addressing a particular content issue such as "radiation as material-like" vs. "radiation as particles in motion". A typical exam would have between four and ten opportunities for students to answer either way on this issue. Most students would write something relatively clear such as "the strawberry would absorb the radiation and become radioactive itself". Such statements were taken as evidence of thinking of radiation as matter-like, and for thinking that radiation causes contamination. Results for all the relevant questions on an exam or HW were then tabulated for each student for each learning issue. A student who answered all of the questions consistently with the particles view would be labeled "differentiated" while another student who answered all or most of the questions consistently with the "radiation as material-like" view would be labeled "undifferentiated" at that time. Students who were not consistent were labeled "in transition". In the Fall semester of 2012, data was collected and analyzed on student views of radiation at twelve different times during the semester. Sometimes data was not available for all 38 research subjects. The graph below shows the percent of students for which we had data who showed they were thinking of radiation as particles in motion, and who no longer thought that radiation contaminates objects.

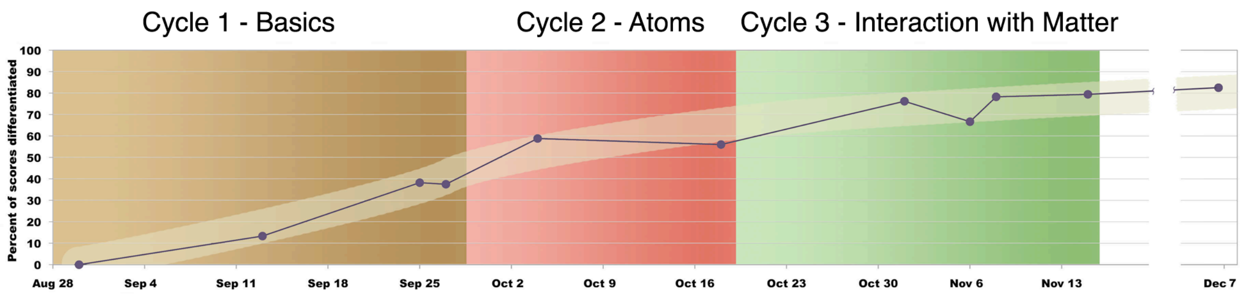


Fig. 1. Percentage of students differentiating radiation from radioactivity in Fall 2012

We interpret these results as showing that while some students changed their thinking fairly early on in Cycle 1, many students did not change their thinking until the later cycles. But once their thinking changed they seemed to continue thinking in the new way. Only twenty percent of the students persisted with the old view of radiation at the end of the semester.

Audience and content

The IiR materials are a complete set of course materials with student documents, teachers guides and handouts. They are the result of multiple iterations of testing and revision, so they should work reasonably well for your students although you may need to modify them for your circumstances. The audience is college students who are not science majors. These materials have been or are being used in "survey of physics" courses, a science course for preservice elementary teachers, and in high school physics courses. Students with more or less background in science will probably need less or more support. Until you gain expertise with the materials we recommend using them as they are written. Things will come up that you can't anticipate the first time around!

Much content is covered, but all of it is there to help students become literate about radiation. It seems to be essential for students to develop scientifically acceptable views of ionizing radiation as high speed electrons, helium nuclei, and photons (packages of energy) emitted from atomic nuclei. If you use the entire materials, most of your students are likely to finish the course with a sound understanding of what atoms are, where radiation particles come from and why they are emitted (except for x-ray machines) and how they do harm. They will be radiation literate.

The course is set up in four modules called "cycles". Each cycle addresses one major area:

Cycle	Title	Content addressed:	Approximate classroom hours
1	Introduction to radiation	Background radiation, randomness, radioactive sources, no contamination, types of radiation, not waves but quanta	18
2	Atoms	Structure of atoms, behavior and properties of ions and isotopes, radiation as subatomic particles, and how alpha, beta, and gamma particles are emitted	14
3	Interaction of radiation with matter	Ionization by radiation, molecule breaking, cell damage, stochastic vs. acute radiation doses, cause of cancer and cancer treatments	18
4	Nuclear power, nuclear waste	Nuclear fission, nuclear reactors, fission products, half lives, relating half lives to random behavior of atoms	18

If you only have time for one cycle, try Cycle 1. It addresses a lot of fundamental issues and is really the starting point for everything else. If you only want to teach about the structure and properties of atoms, Cycle 2 can be used on its own with some modifications.

Try the inquiry approach built into the materials!

If you haven't taught a course using inquiry, trying it for the first time can be intimidating. However, it is well worth generating the courage. Students learn the basic ideas more fully, and the experience of teaching can be a lot more fun. By listening to your students - which is strongly supported in these materials - you will gain a much better sense of what they understand and what they have learned - as well as what they don't know yet.

You just have to have confidence as you go through the materials that your students will learn what the unit is set up to teach. If you stick with the materials, do your best to let the students work things out, and have patience, you will see your students making progress. It's very exciting to watch this happen!

What the course looks like

The IiR materials use three main types of classroom activity - whole class discussion, small group work, and whiteboarding sessions. New topics are introduced as questions to the whole class. The students develop most of the ideas in small groups while working through guided activity documents on computers. These involve a lot of experimentation and demand careful thinking. At the end of a sequence of activities, the class comes together for another whole class discussion to compare their ideas and reach consensus on the ideas that each group has developed.

The materials expect you to take an "inquiry teacher" role in your classroom. Your job as the teacher will be **not** to give answers most of the time, but to introduce questions and activities, focus the discussions on relevant questions, and insist that students rely on evidence and sense-making. You should answer technical questions about how to do experiments or how to interpret a sentence, but you definitely should allow students to struggle with the big ideas until the class has come to agreement on answers. As uncomfortable as it is, struggling with ideas seems necessary for deep, meaningful learning. You need to trust that students really will come up with the answers they need. They will! We have seen this work for many years.

If you have not taught via inquiry before, you will have to develop some new skills but anyone can do this with practice. An extensive teacher's guide is available to help you. It's a low-stakes topic. Try it!

What if I pick and choose just a few pieces?

Many parts of the IiR materials can be useful on their own even when not used with the entire unit. The simulators are educational even if students are not given any guidance, although we recommend that you provide guidance. Some of the activities can be used on their own with small or major modifications and they can still be helpful to your students. The end of this document lists every activity in the IiR materials. However, do not expect the same level of learning as you would get if you were to use the full set of activities. While all students are different, there seems to be a "minimum set of issues" that most students have to work through in order to reliably develop the big ideas about what radiation is. The IiR materials address very little beyond that minimum set so if you take something out, you have to reduce your expectations for what your students will learn.

We have found that the bulk of students in our class did not abandon their old "radiation as matter-like" ideas until some time in Cycle 3! Thus, if you really want students to understand what radiation is, only Cycle 4 is optional.

More about the learning cycle

Because students are the main source of ideas in the classroom, the IiR materials do things differently from a typical classroom. You and the students have to find out at the beginning what they already know and how they are thinking. You and they have to find out their "initial ideas". For example, some students will undoubtedly will answer some questions in ways that imply that radiation is like a germ that can be contagious. You need them to say something about radiation to get this out on the table. As the instructor, you just let them say it and tell them they will be able to test that idea. Next, the students are set to work on developing better ideas. This is the bulk of the work in the classroom. At some point later on the students have new, better ideas but they need a way to be sure that their ideas are okay. So at this point the class negotiates a formal set of statements called the "Main Ideas" that are the most important pieces of information for making sense of that particular topic. These stages are diagrammed below in the "learning cycle" structure.

Initial ideas

Each cycle begins with an "Initial Ideas Activity," which involves a whole class discussion of a question or set of questions. For Cycle 1 and Cycle 2, students fill out the conceptual evaluation as a pretest for that cycle.

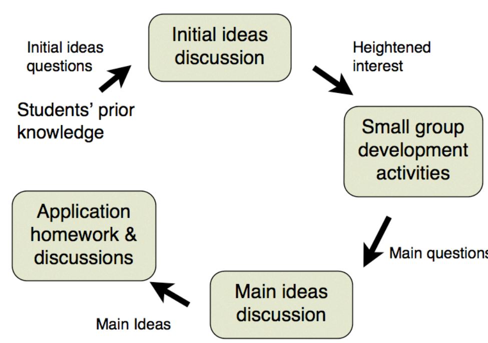


Fig. 2. The IiR cycle structure

This "unpacks" student ideas - it helps students become more aware of their own thinking. You will benefit by finding out how your students are thinking as well.

In an Initial Ideas discussion, each student writes down her thinking before discussing anything with the other members of her group. The teacher then conducts a discussion on the main points **without** answering the crucial questions. Things are left open! Initial ideas discussions are intended to raise issues and ideas, not to settle them. Closure comes later. The Teachers Guide documents go into more detail about how to conduct these discussions.

Development activities

As soon as the class finishes the initial ideas discussion, the students move into small group development activities. Students typically work through these in groups of 2, 3, or 4 sitting at a computer. (It can be done using pencil and paper - this will require some adapation). The computer documents ask students to make predictions, perform specific experiments or design their own, and they present questions that raise particular issues. Cycle 1 involves experiments with geiger counters and sources while Cycles 2 and 3 mostly use computer simulations. The questions and experiments are designed and sequenced to help students develop particular ideas. Each activity is arranged to help students come up with a set of ideas that are scientifically acceptable and that make sense and can explain things. In working through the Development phase, students examine their own ideas in detail and extend, modify, or change them as needed. Be helpful and encouraging to students but let them grapple with their big questions - the groups will eventually develop ideas similar to the ones we want them to have. Sometimes it takes a long time - rely on the teachers' guide documents to know what to expect.

Formalizing the Main Ideas

At the end of the last development activity in a cycle, you will hand out the Main Questions which all groups should be able to answer. The Main Questions cover the major points in the cycle. Once all groups have answers for the main questions, you conduct a whole class discussion in which each of the main questions is talked about and lingering questions are put to rest. In this discussion ideas should come from students, and you can still let groups work out the best way to say something. The goal is that all the groups will agree on each idea - and it almost always works out that way. The end result is that the class should agree on a set of "Main Ideas" that are the content goals. Your job as the teacher is to guide the discussion and offer the special terminology and additional details that students might not have come up with. At the end, you "bless" the ideas that the students have developed and hand out printed copies of the Main Ideas which students keep in lieu of a textbook. Sample versions of the Main Ideas are in the handouts folder for each cycle. This is where students should get closure, and satisfaction.

Applying the ideas

Students will be required to use and extend the Main Ideas in homework assignments. This is part of the learning. Some of the homework assignments are tough, you may have to discuss the answers in class after students work on them. Sometimes it is best to have each group sketch their answer to one question on a whiteboard and present their solution to the class. These whiteboarding sessions seem helpful to students. Note: Homework assignments are also given during the development activities - these are mainly intended to help students think more about a particular issue. They are not graded on correctness but on whether students do diligent work on them. Homework is included in the handouts folders, and the teachers guides say when to hand them out.

Location of the IiR documents

All of the IiR materials are freely available online at http://www.camse.org/radiation/ The complete set, currently about 80 mb, includes student Activity documents, the Teachers Guide documents, Handouts (homework, etc), and simulators.

Cycle 1, Introduction to Radiation: http://www.camse.org/radiation/Rad1-Intro.zip

Cycle 2, Atoms: http://www.camse.org/radiation/Rad2-Atoms.zip

Cycle 3, Interaction of Radiation with matter: http://www.camse.org/radiation/Rad3-Matter.zip

Cycle 4, Nuclear power and nuclear waste: http://www.camse.org/radiation/Rad4-Nuke.zip

Atom Builder simulator: http://www.camse.org/sims/Builder/

Atom Invaders simulator: http://www.camse.org/sims/Invaders/

Tracks simulator: http://www.camse.org/sims/Tracks/

Cloud Chamber video: http://www.youtube.com/watch?v=AMaDqaRzDm4

Equipment list and other documents: http://www.camse.org/radiation/Getting_Started_RBI.zip

Major equipment

Classroom:

The IiR materials require a classroom with lab tables and one computer per group of 3 or 4. A printer is needed.

Key lab equipment needed:

Geiger counters with data collection capability- at least one per group. The documents are written for Vernier's Digital Radiation Monitor and Logger Pro software. You will need the LabQuest or

LabPro interfaces. Other equipment might be usable but you will have to modify the documents to set up the same experiments. Check to see what experiments are done. You need something portable.

Classroom radioactive sources. We use the classroom 3-disk set RSS-3 from Spectrum Techniques. We also have various "found" radioactive sources - uranium-bearing rocks, old lantern mantles, and antique red fiestaware.

Cycle 1 uses special EM field detectors made from tiny guitar amps and coils of wire.

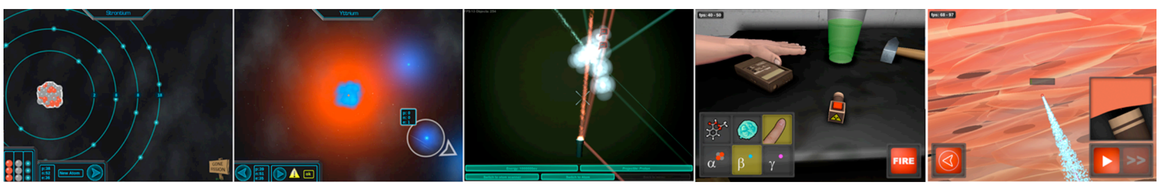
One activity in Cycle 3 uses the Lecture Hall Cloud Chamber made by Supersaturated Environments. If you don't have this you can get by with a video of the cloud chamber.

Cycle 4 uses the Cs/Ba-137 isotope generator from Spectrum Techniques for half-life experiments, and a lot of dice.

A complete list of the equipment needed is at http://www.camse.org/radiation/Extensivelist.doc

A description of where to get things is at http://www.camse.org/radiation/Gettingequipment.doc

Computer simulators



Because students can't directly observe the results of experiments on atoms, the IiR project developed three pedagogical simulators that extend students' abilities to observe (and interpret) atom-scale phenomena.

Many students come to class with very limited understandings of atoms. They often can't use the basic planetary model and they are not prepared to use atoms in explanations. Many do not even remember the basic planetary model, and some confuse atoms with cells! The Atom Builder simulator allows students to build any atom up to element 105 (Dubnium) and observe its behaviors. Ionization is deliberately separated from radioactivity until students are clear on what an ion is and isn't. With the secret access code students can then test unstable atoms. (Secret code: click ten times on the gnome's face!)

Students need to think about how radiation interacts with matter. Using the Atom Invaders simulator students shoot radiation at individual nitrogen atoms or N_2 molecules and observe the results. This simulator also enables a very crude investigation of how ionizing energy varies for each electron removed from the atom.

Connecting the macroscopic scale with the cellular or atomic scales is a tough task for anyone, particularly those who are doing it for the first time. The Tracks simulator supports students in observing and making sense of the similarities and differences in alpha, beta, and gamma radiation, and enables storytelling about the effects of radiation at different size scales. It also promotes understanding of the vast number of ionizations caused by a single alpha or beta, and helps students realize that alphas interact much more strongly with matter than betas do.

Understanding the size scales of different objects is also supported by the University of Utah's Cell Size and Scale zooming applet.

Detailed list of activities:

The IiR materials are arranged in four cycles. The first cycle - on basics of radiation - introduces detectors, background radiation, radioactive sources, distinguishing ionizing from electromagnetic radiation, waves vs. quanta, and distinguishing types of ionizing radiation via shielding experiments. Most students begin with very vague and dysfunctional ideas about radiation - very few if any think of radiation as high speed subatomic particles. At the end of Cycle 1 students conclude that radiation is tiny high speed "quanta" traveling sporadically from certain objects, and alpha, beta, gamma have been introduced.

The second cycle is about atoms. We found that our students (even those who had taken chemistry!) really didn't understand atoms well at all, and this was getting in the way of understanding atoms as sources of radiation and as victims of radiation. So Cycle 2 introduces the structure of atoms, what ions are, goes into details about isotopes, and the nuclear origins of radioactivity.

Cycle 3 focuses on ionization by radiation particles, and on the health effects of radiation. Students develop a microscopic model for the effects of radiation on matter and are asked to extend it to living things, and they read about the macroscopic effects of radiation poisoning and cancer.

Cycle 4 is about nuclear fission, nuclear power, halflives, the fundamental reason why radioactive materials have halflives, and nuclear waste.

Interleaved with the content are opportunities to teach about the nature of scientific knowledge and the history of radiation science. Homework assignments and readings address historical developments such as Becquerel's discovery of radiation. The Seeds activity, the structure of the materials and "evidence assignments" introduce students to the character of scientific knowledge, including its experiment-based status, the question of truth in science, and the necessity of distinguishing between observations and inferences when talking about the natural world.

The following brief descriptions are written to give you a general sense of what happens in the materials. Each activity has a two or three page teachers guide document as well.

Cycle 1 (Times are approximate and will vary with your students and your approach):

0.1 The Seeds (160 minutes including discussion) This is a warmup / framing activity for the first day of class. It gets students used to participating in class. And it's useful for talking about science!

Students invent theories of (not real) seed behavior to experience a model of how science works. This activity - a participatory parable - introduces students to the new (and risky) job of proposing explanations with insufficient information, and testing these explanations based on data or observations.

This activity also helps students distinguish between "accepted facts" versus scientific knowledge. Students tend to accept scientific claims about reality without questioning them or wondering where they come from. We want to promote a healthy questioning attitude.

Also, the first day of class plays a crucial role in setting the stage for the rest of the semester and encourages students to go along with how the class is taught. This activity and its accompanying homework are very helpful. If you do not do the Seeds activity, you should do some other things that warm the students up to a course in which they will be expected to speak up and take social risks.

More ideas on "Framing the Interactive Engagement Classroom":
http://www.colorado.edu/sei/fac-resources/framing.html

1.0 Radiation initial ideas (70 minutes including discussion) Students fill out the Radiation Basics questionnaire on what they know about radiation. This data will be useful to you! The class discusses the different questions. This discussion puts ideas "on the table" so that students can talk about them during the rest of the cycle and eventually decide what makes sense and what doesn't. However, at this point the instructor only listens to ideas and clarifies them, but does not say whether any ideas are correct or not.

1.1 The Radiation Monitor (170 minutes) Students work out basics of background radiation - it comes in quanta, it is sporadic (random in time) but it seems to have an average value more or less. It seems to be about the same everywhere. Students take a little longer to do this activity than they will later - they have to get used to the scheme.

1.2 Variation (150 minutes) Introduces ideas of randomness and motivates a method for comparing averages. Because counts of radiation vary from minute to minute, we need a way to decide whether two different averages are different just from random variation or from something actually being different. The method proposed is to compare one average plus or minus its standard deviation with the other average. If the second average falls within the range of the first average (or vice-versa) then the two averages could have arisen by random variation. You can teach about t-tests instead if you prefer - this method was intended to be more transparent.

1.3 Sources of Radiation (150 minutes) Students discover radioactive sources in the classroom and work out the approximate hazard of radioactive disk sources. Although the count rates for the radioactive disks seem high, we accumulate large amounts of radiation "counts" from background radiation no matter what.

1.4 Radioactive Contamination (50 minutes plus prior setup) Students test whether a radiation source can make something else radioactive. It doesn't! This is surprising to many students.

1.5 More detectors (90 minutes) Students use an electromagnetic field detector to find radiation coming from electrical devices like microwaves and cell phones. This leads to distinguishing between EM radiation vs. "countable" radiation. (It's probably better not to introduce the term "ionizing" radiation until Cycle 3). Then following an idea from researchers Eijkelhof and Millar, students go through a "circus" of different setups, each of which involves a source, a particular type of radiation, and a detector. This has two goals: to clarify the source - radiation - detector model of radiation for different types of radiation (sound, light, IR, EM, and Ionizing) and to raise questions about the characteristics of radiation. Not all of the questions are answered - Cycles 2 and 3 help settle questions about whether the radiation is present as radiation beforehand, and whether the radiation remains on the victim after it hits the victim.

1.6 Types of Countable Radiation (90 minutes) Students identify three types of countable radiation - alpha, beta, and gamma based on their penetrating power. The difference between count rate and penetrating power is also clarified - a high count rate does not necessarily lead to high penetrating power.

Settling Class Main Ideas on Radiation (100 minutes) The class discusses and agrees on Main Ideas about radiation.

Dealing with waves: Throughout this cycle, some or most of your students will be thinking that all radiation is composed of waves, especially if they don't know what waves are! The teacher's guide suggests questions and demonstrations you can do to help students decide whether the radiation quanta are waves or not.

Cycle 2: Atoms

Our students do not initially understand atoms well at all. An entire cycle on atoms is needed to help students remember the structure of atoms and understand ions and isotopes.

2.0 Initial Ideas (60 minutes) Students are fill out the conceptual evaluation on atoms. They draw pictures and are asked various questions about the structure and behavior of atoms. A brief classroom discussion is intended to help students realize that they are all pretty much in the same boat with regard to confidence about atoms. Even some students who took chemistry will show that they don't understand atoms.

2.1 Tape (Charges) (50 minutes) A few short experiments with sticky tape introduce electrical repulsion and attraction. Students need to have this in mind when they start thinking about atoms.

2.2 Atoms (140 minutes) Students work out the structure and behavior of atoms and ions by playing with the Atom Builder simulator. The simulator represents the orbital model of atoms and enables students to build any atom from hydrogen to dubnium. Students work out relationships between the number of protons, the number of electrons, the atomic number and the element name. Students can test atoms in a separate "testing world" where they encounter semi-realistic behavior that depends on the ionization state of the atom. To help students distinguish between ionization and radioactivity, the simulator does not allow students to make radioactive atoms. However, students do puzzle over the seeming non-role of neutrons.

2.3 Neutrons in Atoms (120 minutes) Uses the Atom Builder to address the role of neutrons in forming different isotopes but students to not see nuclei explode yet. The isotope naming convention is presented.

2.4 Risky Nuclei (140 minutes) Again using the Atom Builder with expanded capabilities, students discover that non-naturally occurring atoms (nuclei) will explode and emit stuff. The class tentatively identifies the high speed particles with the radiation they detected in Cycle 1.

2.5 Counting Neutrons (140 minutes) Students study the effects of building large nuclei and changing the number of neutrons. They identify two major processes: Large nuclei sometimes emit a clump of 2p2n, which is a high speed helium nucleus. (But this is not called alpha yet!) Nuclei with "too many neutrons" will convert a neutron to a proton and emit an electron from the nucleus. (This is not called a beta yet!) These phenomena are tough to work out but students do reach these conclusions. Also, students note that there is almost always a second particle emitted - the "packet of energy" - that is not composed of electrons, protons, or neutrons. Neutrinos are not discussed.

2.6 What are abg? (50 minutes) While the class has identified three types of particles coming from nuclei, students have not connected these particles to alpha, beta, and gamma radiation. Groups use the Atom Builder once more to build the nuclear species that are in the actual disk sources: Polonium 210, Strontium 90, and Cobalt 60. They then match the particles emitted to the known radiation from the disks.

Settling Class Main Ideas on Atoms (80 minutes) Groups of students propose main ideas about atomic structure, ions, and the origins and characteristics of radiation. You can add in neutrinos if you like.

You would think this is enough to get students to accept the idea of radiation as high speed particles that can't cause contamination, but it isn't. Many students need to work with these ideas for longer. Cycle 3 helps.

Cycle 3: Radiation and matter

3.0 Initial ideas - Students are asked about relative sizes and roles of atoms, molecules and cells. Other questions ask about "radiation sickness" and whether this causes a person to be radioactive or mutated.

3.1 Radiation and atoms Using the Atom Invaders simulator, students ionize atoms by shooting various particles at them, and see that different types and energies of radiation have different effects, but the only effect is removal of electrons. This is when the name "ionizing radiation" finally can be introduced. Any sooner and students will not know what it means.

3.2 Many atoms Using the Tracks simulator, students investigate the effects of single radiation particles passing through matter at the macro scale, the cell scale, and the molecular scale. They also are asked to think about the presence of atoms and molecules in matter and to compare them with cells.

3.3 Cloud chamber Students observe tracks in a cloud chamber and connect their observations to ideas about ionizing by radiation. This is harder for students than you might expect! If you don't have a cloud chamber, use the video provided here, or download the high resolution version.

3.4 Acute Exposures Introduces immediate effects of radiation damage, students develop a mechanism for cell damage by radiation and test the range of betas and gammas in water which is a proxy for living tissue.

3.5 Stochastic Effects Introduces long-term effects of radiation damage, students are asked to develop a model for how low levels of radiation damage can induce cancer without any apparent harm. Also explains how radiation can be used to kill cancerous tumors.

3.6 Settling Class Main Ideas for how radiation affects health The class comes to agreement on the relationships between atoms, molecules, and cells, and clarifies the effect of radiation - it ionizes molecules which damages cells. The goal is for students to be able to construct a coherent story line about the emission of a radiation particle from the source atom to the ionization of a victim atom to cellular damage to health effects.

Cycle 4: Nuclear waste

4.1 Gone Fission Students first use the Atom Builder to make sense of spontaneous fission, then they use the PHET nuclear fission simulator to investigate neutron-induced nuclear fission and the fission chain reaction. They account for neutrons and protons in the fission reaction, and use the online Chart of the Nuclides (http://www.nndc.bnl.gov/chart/reColor.jsp?newColor=dm) to identify fission daughters and find out that most fission daughters are neutron-rich and therefore radioactive.

4.2 Nuclear Power (TBD) This activity will introduce reasons why nuclear power is desirable, including comparing the energy released by fission versus the energy released by burning fossil fuels, and the relative production of CO_2 for each process. It also will describe the general structure of nuclear power plants and the reason why fuel rods must be removed from the reactor before the uranium is used up.

4.3 Lifespan of radiation This activity uses the 137Cs/137Ba isotope generator to dispense samples of a short-lived radioactive isotope. Students measure radiation from 137Ba* and calculate half-times of the radiation counts as a way of identifying half-lives. Although we use Logger Pro to fit an exponential function to the data, there is little discussion of the exponential function. Instead, "half-life" is defined as "the time for something to decrease by half" and it only exists when the times to decrease by half (called "half times") are always the same.

4.4 Atoms timing Students need to think more carefully about how the random behavior of atoms can result in the half-life phenomenon. To model this, the class as a whole rolls thousands of dice (actually each group rolls a dozen dice multiple times) and compare results with radiation data. Groups use this data to generate a theory of how half-life behavior arises from a simple set of rules applied to radioactive atoms. Students will tell you that they didn't understand half lives until they did this activity.

4.5 Nuclear waste Students work through the creation of fission daughters again, and work out the time scale and progression of radiation emission from fission daughters.

Settling Main Ideas about nuclear fission and nuclear waste Students propose explanations for why nuclear fission creates radioactive fission daughters, what a half life is, why some materials seem to stay radioactive a long time, and why reactors must be maintained even when shut down.