Communicating Research to the General Public

At the March 5, 2010 UW-Madison Chemistry Department Colloquium, Prof. Bassam Z. Shakhashiri, the director of the Wisconsin Initiative for Science Literacy (WISL), encouraged all UW-Madison chemistry Ph.D. candidates to include a chapter in their Ph.D. thesis communicating their research to non-specialists. The goal is to explain the candidate's scholarly research and its significance to a wider audience that includes family members, friends, civic groups, newspaper reporters, program officers at appropriate funding agencies, state legislators, and members of the U.S. Congress.

Over 50 Ph.D. degree recipients have successfully completed their theses and included such a chapter.

WISL encourages the inclusion of such chapters in all Ph.D. theses everywhere through the cooperation of Ph.D. candidates and their mentors. WISL is now offering additional awards of $250 for UW-Madison chemistry Ph.D. candidates.

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The dual mission of the Wisconsin Initiative for Science Literacy is to promote literacy in science, mathematics and technology among the general public and to attract future generations to careers in research, teaching and public service.

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Spent Nuclear Fuel Attribution using Statistical Methods: Impacts of Information Reduction on Prediction Performance

by

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For onkwehshón:'a (the People)

For iokhih'nisténha ohóntsia (Mother Earth)

For ohneka'shón:'a (the Waters)

For kentsionshón:'a (the Fish)

For tsi shonkwaienthó:wi (the Plants)

For kaien'thóhshera (the Food Plants)

For ononkwa'shón:'a (the Medicinal Herbs)

For kontírio (the Animals)

For okwire'shón:'a (the Trees)

For otsi'ten'okón:'a (the Birds)

For owera'shón:'a (the Four Winds)

For ratiwé:ras (the Thunder Beings)

For kionhkehnéhkha karáhkwa (Brother Sun)

For ionkhih'sótha ahsonthenhnéhkha karákwa (Grandmother Moon)

For otsistanohkwa'shón:'a (the Stars)

For kaié:ri niionkè:take (the Four Beings)

For shonkwaia'tíson (the Creator)

éhtho niiohtónha'k ne onkwa'nikón:ra (and now our minds are one)

ABSTRACT

Nuclear forensics is a nuclear security capability that is broadly defined as material attribution in the event of a nuclear incident. Improvement and research is needed for technical components of this process. One such area is the provenance of non-detonated special nuclear material; studied here is spent nuclear fuel (SNF), which is applicable in a scenario involving the unlawful use of commercial byproducts from nuclear power reactors. The experimental process involves measuring known forensics signatures to ascertain the reactor parameters that produced the material, assisting in locating its source. This work proposes the use of statistical methods to determine these quantities instead of empirical relationships.

The purpose of this work is to probe the feasibility of this method with a focus on field-deployable detection. Thus, two experiments are conducted, the first informing the second by providing a baseline of performance. Both experiments use simulated nuclide measurements as observations and reactor operation parameters as the prediction goals. First, machine learning algorithms are employed with full-knowledge training data, i.e., nuclide vectors from simulations that mimic lab-based mass spectrometry. The error in the mass measurements is artificially increased to probe the prediction performance with respect to information reduction. Second, this machine learning workflow is performed on training data analogous to a field-deployed gamma detector that can only measure radionuclides. The detector configuration is varied so that the information reduction now represents decreasing detector energy resolution. The results are evaluated using the error of the reactor parameter predictions.

The reactor parameters of interest are the reactor type and three quantities that can attribute SNF: burnup, initial ^{235}U enrichment, and time since irradiation. The algorithms used to predict these quantities are *k*-nearest neighbors, decision trees, and maximum log-likelihood calculations. The first experiment predicts all of these quantities well using the three algorithms, except for *k*-nearest neighbors predicting time since irradiation. For the second experiment, most of the detector configurations predict burnup well, none of them predict enrichment well, and the time since irradiation results perform on or near the baseline. This approach is an exploratory study; the results are promising and warrant further study.

1 LET THEM EAT STEAK: A CHAPTER FOR THE NON-SCIENTIST

This chapter was written to convey my PhD work to the general public and was supported by the Wisconsin Initiative for Science Literacy (WISL). I have much gratitude to WISL and Prof. Bassam Shakhashiri for the editing assistance and the opportunity.

Writing this chapter is a also result of me keeping a promise to myself, and so despite its cheesy approach to telling a tale of science, it is a beautiful and important moment for me. I have a lot of people to credit for helping bring this story from a parallel universe into reality: Anna Stephenson for the illustrations and helping me convert my graphics from sterile science to adorable art; Robin Kinchen Cenac (and Reya!) and Louise Opotowsky for overall creative guidance and for suffering through highly technical explanations of my work to prepare me for writing this chapter; Prof. Paul P.H. Wilson, Almost-Dr. Kalin Keisling, Dr. Dinh Truong, and Dr. Richard Rojas Delgado for feedback and suggestions on my fake country names; and last, never least, but always the littlest, Ninjita Binjita, for the all-important role of lap warmer.

Narrator:
Welcome, curious companions! Our good friend has got a tale to tell. But they cannot tell this story on their own, so they asked me to give you some background and science along the way.

Be warned: the country names are drawn from a parallel universe with different nations and international relations. Any similarities to countries that exist in this universe are purely coincidental. Additionally, there are fantastical details throughout the tale, and the capability of our curious companions to decipher between fantasy and science is presumed. This parallel universe also doesn't have an Earth with the same climate crisis, so the steak in this analogy is definitely from a happy cow on a regenerative farm.

Background & Introduction

Many underappreciated jobs keep a civilization functioning. For example, excluding

New Orleanians and other People of the Pothole (yes, New Orleans exists in the parallel universe), you probably don't think about how you hold the expectation that your roads are drivable. There are those responsible for moving your garbage out of sight and mind, there are also people who clean up roadkill, and there are those who clear the shards of a car accident with fascinating speed. In fact, when any civic role functions well, it isn't noticed. It is an odd result of a well-functioning society that the most essential components remain unseen until they no longer function. Jobs like this exist at the federal level, generally unseen, because they are so crucial they regularly get bipartisan support. This is a story about *those* people.

Now to our friend…

> Imagine the scene: they were sitting in their backyard in perfect weather, breeze blowing, flowers flowering, and chipmunks chirping, eyes closed as the sun warms their skin. Suddenly they felt a chill, and opened their eyes to a dark sky.
>
> Except it wasn't a dark sky, it was a drone hovering over them with a package for delivery! C'est mystérieux! They hadn't ordered anything. What could it be?
>
> Why, it was a package of nuclear material *(Narrator: well-packaged, because we are not irradiating our friend)* delivered anonymously. Turns out, they unknowingly intercepted the attempted smuggling of nuclear material to construct a weapon inside the borders of United Fissions of Uranium (the UFU). And now our friend is officially in the middle of an international drama. What to do? Who to tell?

Narrator:
I actually don't know who they should have told; federal jurisdictional decisions for nuclear incidents is not the drama being told today. But the authorities quickly found out and figured that out for themselves.

Our friend's day is quite ruined. Illustration by Anna Stephenson

This turns out to be a misdelivered package, because nuclear terrorists are people too...that sometimes make typos. The UFU authorities believe that there are many more packages on their way to different locations, but having no intel on where to intercept them, they need to know where this material came from to locate the terrorist group responsible. They need nuclear security experts, and FAST.

Narrator:
Enter: nuclear security. This is not to be confused with nuclear safety, that is, making sure nuclear power reactors behave and do not have accidents that harm the environment

and the beings in it—a more-than-worthy effort, but not the one being discussed here. The nuclear security enterprise instead focuses on preventing or mitigating undesirable outcomes of a different variety, like nuclear terrorism. Nuclear security's goal is keeping all of the nuclear material in the world inside a regulatory pipeline, so none of it gets into the hands of people who want to do others harm.

In this universe:
A high profile example of nuclear security at work, at least on a diplomatic level, is the Joint Comprehensive Plan of Action[1], better known as the Iran nuclear deal. Personal opinions (if you have them) and recent news (if you've seen it) aside, its purpose is to keep a closer eye on the country to be sure they aren't developing the capabilities necessary to make weapons. Another part of the nuclear security effort is a strong nuclear forensics capability. Nuclear forensics begins **after** a nuclear incident occurs, which sadly, happens. This incident can be some intact material drone-delivered to a friend by mistake, or it could be something even worse, like the detonation of a nuclear weapon. Just in 2019, the International Atomic Energy Agency confirmed malicious intent for six incidents of trafficked nuclear material[2].

Most might think of forensics as catching a murderer, but this is more like catching the nuclear smuggler. Given some nuclear material (a body) and composition of the material/how it was encased and transported (the clues around it like blood and fingerprints), how/from where was the nuclear material obtained and/or smuggled (what conclusions can be drawn about the murder)? In both situations, forensics work ideally leads to blaming, with court-admissible proof, someone for the illegal act. Fingerprints of humans are important to a murder investigation, and likewise, there are fingerprints of nuclear materials that can provide their point of origin and/or where they were processed.

> Slight correction: They need **nuclear forensics** experts, and FAST.
>
> These UFU authorities are in luck, since our friend happens to be a hobby

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[1] For more information on the JCPOA, see this fact sheet

[2] Here is the 2020 document that contains this information

nuclear forensics scientist! As a citizen scientist, they cannot use actual nuclear materials or well-equipped laboratories to test their methods and ideas. Our friend instead uses their software development and simulation skills to study their favorite topic of attributing mysterious nuclear materials to their point of origin. This is now their chance to unveil a research method to the authorities and see if they can help prevent a nuclear weapon from being detonated in the UFU in time.

But the authorities are not sure. Some experimental method developed by a ~~grad student~~ hobby scientist surely wouldn't work? Also, it's not validated, so it wouldn't hold up in court. But the race to save lives is on. "What," they ask, "do ya got cookin'?"

Narrator:
I'll tell you all about what our friend has cookin': some steak. But hold on, I'll get there in a minute.

From a visual inspection, the nuclear material in question has been determined to be nuclear fuel after it's been loaded into, used in, and removed from a nuclear reactor. By performing some to-be-discussed nuclear forensics approaches on this material, we can figure out all of the details of this fuel related to its creation, time in the reactor, and how long it has been out of the reactor.

First, I need to define some terms for you. There are four main concepts that are covered: *reactor type*, *burnup*, *enrichment*, and *time since irradiation*. Ideally, the process of determining these parameters can pinpoint a sample of nuclear fuel to the exact reactor it came out of!

Let's consider the nuclear fuel as food, specifically, steak. We can think of the reactor as the type of pan our steak was cooked in. If it's cast iron, it'll make a different steak than a $10 nonstick pan that's only nonstick for 3 uses (the parallel universe shares some similar woes). The same is true for nuclear fuel; it looks quite different depending on which reactor type it spent time in. Our friend focuses on three main types of nuclear

If you imagine nuclear fuel as steak, you might be able to figure out the reactor that made it! Illustration by Anna Stephenson

reactors, called pressurized water reactors (PWRs), boiling water reactors (BWRs), and pressurized heavy water reactors (PHWRs)[3]; different countries use one or a mix of these three main technologies. (More than these three exist, but these are the ones our friend wants to focus on.)

There's also a measurement called burnup. In steak-talk, this is how well-done it is (more accurately, it is how much energy your steak produces, but it is more "well-done" as it cooks longer and produces more energy), and would be measured in energy produced

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[3] We won't cover any details about these reactors here, but if you're curious about different types of nuclear reactors, here is a great summary.

per unit of raw steak. In nuclear-talk, it's measured in energy (mega- or gigawatt-days) per metric ton of initial uranium (MWd/MTU or GWd/MTU).

Next, the enrichment, meaning % uranium-235 (^{235}U) enrichment, which refers to how much of this type of uranium is in the nuclear fuel when it's freshly made. A lot of the time, nuclear engineers refer to a specific element from the periodic table with a mass number attached, like ^{235}U, as nuclides, because the concept of nuclides emphasizes nuclear properties, which can differ drastically even though they are the same element on the periodic table. "U" is shorthand for uranium, and the mass number 235 refers to the number of protons (92) plus neutrons (143) in the nucleus of the atom. The protons have a positive charge, and the neutrons have no charge; the protons are balanced by the negative charge of an equal number of electrons, but we aren't worried about those right now. ^{235}U is a special nuclide that nuclear engineers call *fissile*[4]: when it absorbs an extra neutron, it splits into two atoms and releases some energy. When this energy is harnessed into our electrical grid, it's great, but that energy can also be harnessed into a weapon, which is not great. This is like the calorie content or fat content of your steak. The more fat, the more calories, and so the more energy it can supply. In nuclear fuel, more fissile material in the form of a higher ^{235}U enrichment means that the fuel can provide more energy than a fuel of lower enrichment. Uranium naturally has 0.7% ^{235}U in it, but commercial nuclear fuel is commonly enriched up to 5%.

Last, the time since irradiation measures how long the nuclear fuel, or steak, has been cooling after it leaves the reactor, or pan. Nuclear fuel is intensely radioactive when it leaves the reactor, which produces a lot of heat, so it needs to cool off for a few years to be able to be stored longer term without heat dissipating measures (which is submerging the nuclear fuel in water; think of the fuel as taking a several year vacation in a swimming pool). This is just like our steak needing to rest a little before it's consumed. And that's about as far as this metaphor can go, because aside from some recent Godzilla movies, I don't think any of us are eating nuclear waste (in this universe, at least).

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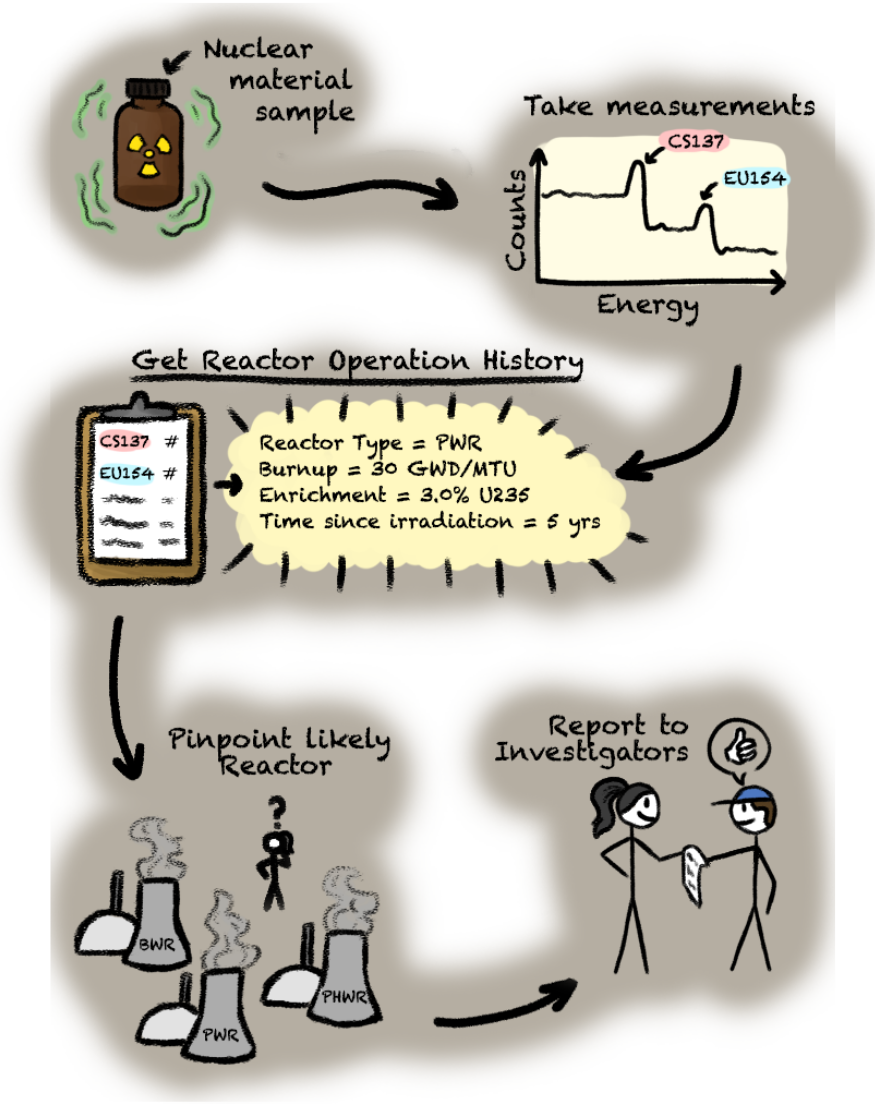
[4] For more information on nuclides and what fissile means, check out this link.

If a nuclear material spent time in a nuclear reactor, these four parameters, part of what we will call the reactor operation history, are important to identifying where it came from. Next, we will talk about how identifying where it came from can happen in an investigation.



It's as simple as this ↑. Illustration by Anna Stephenson

After some of-unknown-origin nuclear material believed to be from a reactor enters our consciousness, some measurements will be taken by technicians working with the government. For example, this could be something called *gamma spectroscopy*, which is pictured in the process below. This detector measures a type of radioactivity called gamma rays[5], and gamma rays have different energies. So the material is just sitting there spitting out gamma rays left and right and up and down and the detector is just sitting there measuring the ones that hit it. It collects counts of gamma rays associated with an energy; this is called a gamma spectrum. Gamma rays of certain energies are known to come from certain nuclides.

Knowing how much of certain radioactive nuclides is in a material can tell us about the reactor operation history: the reactor type (pan), burnup (doneness), enrichment (fat), and time since irradiation (rest time). After determining these parameters, a specialist can pinpoint a specific reactor somewhere in the world (via access to a reactor history database) that created the material and investigators can use that to move forward with their work.

Methodology

In the time it took to get through the lesson above, a foe had enough time to arrive on the scene: an official government scientist. This scientist has a different priority: precision over speed. Our friend's research is driven by "how fast can I get an answer?", whereas the scientist is driven by "what's the most correct answer?" These two priorities in this situation are at odds, but both equally important. The authorities need an answer, and fast, but it needs to be the right one because otherwise many UFU lives are at risk.

Our friend was in the middle of telling the authorities about their fast nuclear fuel-identifying machine learning approach when this scientist arrived, so they got to listen in:

"Machine learning is a field under the umbrella of artificial intelligence, which

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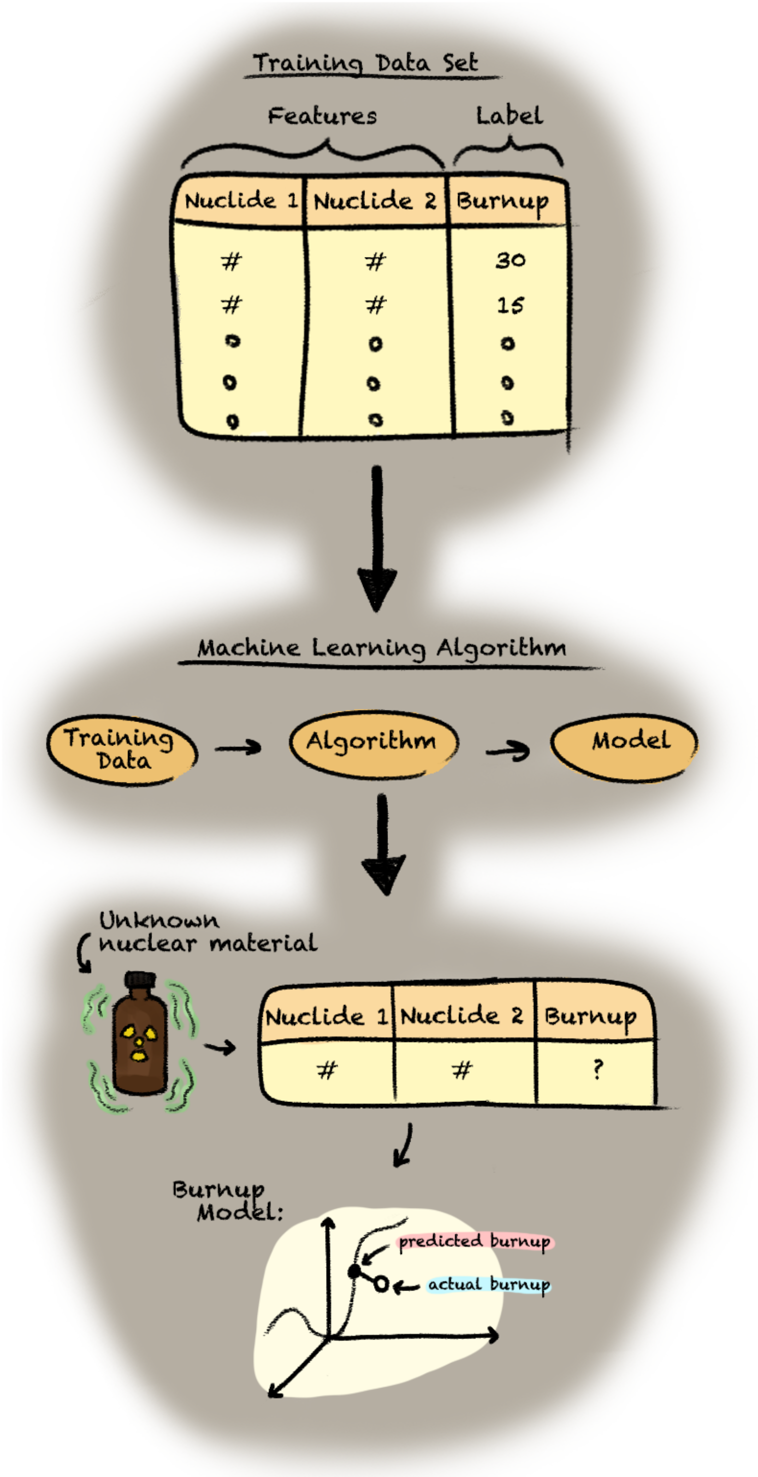
[5] Gamma rays are really cool, and if you read this article, you'll think so too!

allows computers to imitate human behavior. Scientists are using machine learning in many fields to solve complex problems, and so I wanted to see if it could be useful in my favorite area of study: nuclear forensics."

Pointing to the top of the diagram, they say, "So, I first simulated hundreds of thousands of examples of nuclear fuel scenarios: different reactor types, many levels of burnup, different levels of ^{235}U enrichment, and times since irradiation spanning up to 16 years. Each simulation gives me lists of nuclides and their measurements that are important to determining those four parameters. Machine learning professionals call these lists of nuclides the *features*, and the parameters are *labels*. All together, it's called a *training data set*."

Pointing to the middle, "Next, this training data is put into a *machine learning algorithm*[6], which is how people teach computers to teach themselves with some software method. Using the training data set, the algorithm creates a model, which is usually a model we can't see or understand as humans. They are quite secretive creatures, don't you think? Anyway, there are many different types of algorithms, and I have tested out some simple ones to see if this approach is even remotely feasible. These also happen to be the less-secretive type of algorithms so we can understand what the models are doing. One seems to work really well, called maximum log-likelihood (MLL) calculations[7], and I think it's good enough to use to save UFU."

Last, they point to the bottom of the diagram. "So now we have the model. If we take the same measurements that exist in the training database features, then we can use the model to give us a predicted label, in this case burnup. But because I'm doing this experimentally, I know the actual label because I simulated this unknown nuclear material. So in this way, I can measure the prediction errors and refine my method."



Again, it's as simple as this ↑. Illustration by Anna Stephenson

The UFU authorities' eyes glazed over, but the scientist was excited. They were thinking, "My oh my, we could use this! I have a database just like this of the most perfect simulated nuclide measurements that I can use back at the lab! I never really knew what to do with it, so I took a screenshot of a few entries and used it as my desktop background; databases are beautiful."

But our friend didn't think the scientist could take the proper measurements in time. Our friend uses this method with a different kind of training set, one that is created by simulating detectors that can take measurements in minutes *(Narrator: remember the gamma spectroscopy from above?)*, with the expectation that this would help in a real world scenario like this one. The gamma detectors measure the radioactivity of the sample, which is more difficult to get a direct answer from than the scientist's method in the lab, but our friend is all about speed. The measurements the scientist needs to take to match the sample with their training database involve dissolving the material and making many different measurements of the nuclides using a technique called mass spectrometry[8]. It gives super accurate results that will do well with the machine learning method, but the measurements take weeks.

They fought about this for about an hour, which was silly because our friend could have taken the gamma measurements in a fraction of that time and been off to use their machine learning model. But, tensions were high, egos were flaring, and everyone wanted to save lives.

The UFU authorities deglazed their eyes and looked at each other, then at our friend, then at the scientist. After some telepathic decision making, they said, "We choose……"

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[6] For a better introduction to machine learning, read this!

[7] If you have institutional access to journals, here's the method's first paper.

[8] I tried to find a non-company-affiliated source that explained this simply, but failed. This is a good explanation, though, if you're curious about mass spectrometry.

Narrator:
Now, you, curious companion, must choose your own adventure. Do we use our friend's speedy strategy or do we trust the scientist's careful course of action? Remember, we want to be fast, which our friend can most likely do, but we also want to be right, which the scientist can most likely do.

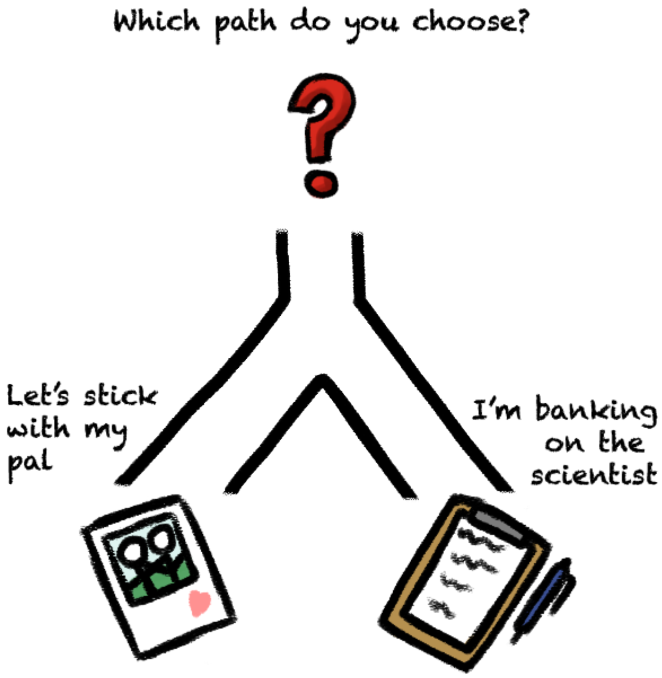
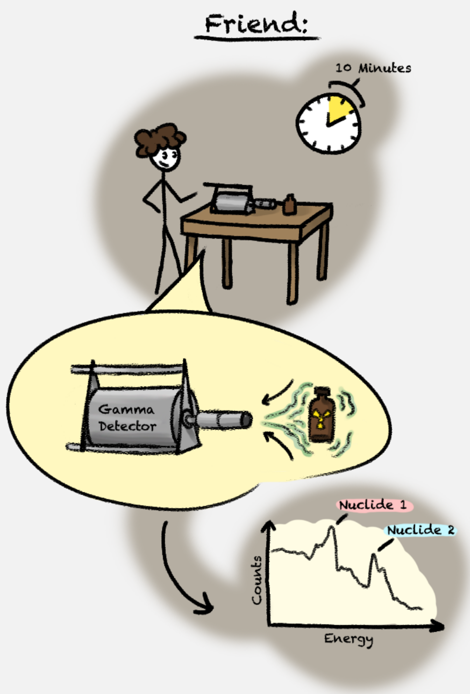


Illustration by Anna Stephenson

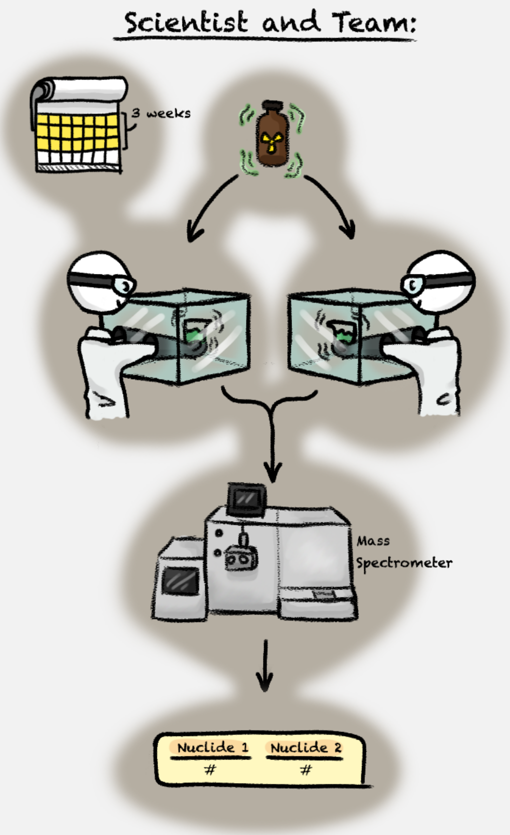
"...our friend!" Now the race is on to measure the material with a gamma detector and predict the fuel's reactor operation history. For a hobbyist, our friend has a pretty great gamma detector: a portable high-purity germanium detector. It can detect the gamma rays very precisely, and our friend always wants to use the best detector they can get their hands on.

"...the scientist!" Now the scientist takes the nuclear fuel to start making measurements. Back in their fancy state-of-the-art lab with all the mass spectrometry equipment a radiochemist could ever dream of, the scientist and their team get started. One week goes by, two weeks go by. And by the third week the scientist and their team had measured 29 nuclides in the nuclear fuel sample to high precision!



This process doesn't require advanced training. Illustration by Anna Stephenson

Using the technical assistance of the UFU authorities, our friend was able to protect themself against radiation and take the sample out of its packaging to get the best measurements possible. They let the detector measure the sample for 10 minutes, et voilà: a gamma spectrum of the sample. Our friend then took the gamma spectrum and compared it against their machine-learned model that was created using a training set composed of 450, 000 simulated gamma spectra of different types of nuclear fuel. And out popped an answer:



This process is complicated, but here are some snapshots. Illustration by Anna Stephenson

Now they were ready to borrow our friend's machine learning method to predict the parameters of the reactor operation history. The scientist then took the list of 29 nuclides and their measurements and compared that information against their machine-learned model that was created using a training set composed of 450, 000 of the exact same 29 simulated measurements of different types of nuclear fuel. And out popped an answer:

Results

Reactor Type	BWR
Burnup	44.02 GWd/MTU
Enrichment	2.04 % ^{235}U
Time Since Irrad	5.34 *years*

“Ok! We got it!” said our friend. Given these values, some of the UFU authorities specializing in worldwide reactor operational history databases were able to determine this came from a reactor in the Democratic People’s Republic of Thoria (DPRT).

This made sense to everyone because the DPRT had been a threat for some time. Everyone knew their missiles couldn’t get to the UFU, so they must have concocted a different plan.

It was a matter of hours before the UFU had hundreds of DPRT conspirators in custody. With the culprits contained, the drone-delivered material didn’t make it to the bomb assembly location, and the day was saved!

...Except, three weeks later, the capital city of Curiumville was bombed.

Reactor Type	BWR
Burnup	44.02 GWd/MTU
Enrichment	4.11 % ^{235}U
Time Since Irrad	4.65 *years*

“Ok! We got it!” said the scientist. Given these values, some of the UFU authorities specializing in worldwide reactor operational history databases were able to determine this came from a reactor in ...GASP!

The Commonwealth of Puerto Plutonio, a Territory of the UFU?! This made no sense! We thought they liked being colonized!

It was now a rush to track down the conspirators since there wasn’t much intelligence data on them. The UFU was scrambling.

And in the middle of the scramble, the capital city of Curiumville was bombed.

Narrator:
Now, curious companion, you are both permitted and encouraged to read the other adventure.

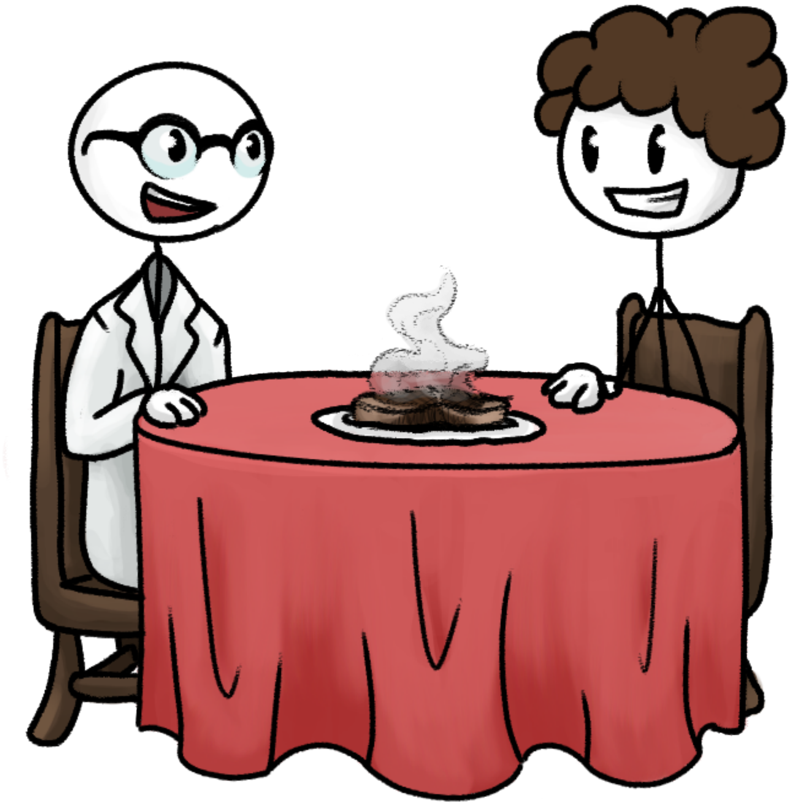
After weeks went by the UFU authorities with the help of the scientist were able to confirm the actual parameters:

Reactor Type	BWR
Burnup	44.02 GWd/MTU
Enrichment	4.11 % ^{235}U
Time Since Irradiation	4.86 $years$

Our friend's experimental machine learning method isn't so bad for a method developed with little resources! Their gamma spectroscopy-based approach predicted the correct reactor type and burnup. Most significantly, though, their method did not predict the ^{235}U enrichment well, and this is what led to the false blame on the DPRT. (The time since irradiation was also 6 months too long, but didn't heavily impact the false attribution like the enrichment did.) The scientist's mass spectrometry-based approach was clearly more accurate for all four parameters. The reactor type, burnup, and enrichment were correctly predicted. Although the time since irradiation was off by 2-3 months, this error didn't result in any false blame being allocated.

In both versions, luckily, the bomb didn't detonate and no one died. It was too rushed of a job, and with the nuclear test ban treaty, no one actually knows their nuclear weapons WILL work. You didn't think our friend's tale was going that dark, did you?

> "Hey," the scientist said to our friend, "I'm famished." Our friend said, "Oh goodness, me too!" They looked at each other, and after some telepathic decision making, agreed on a nice steak.



The end. Illustration by Anna Stephenson

Discussion & Conclusions

This machine learning-based research protocol is designed to answer the question: *How does the ability to determine forensic-relevant spent nuclear fuel attributes using machine-learning techniques degrade as less information is available?* The dissertation written after this chapter answers that in much more detail than the two scenarios presented here, but I hope to have communicated the basics of what I'm doing to a general audience. I actually don't use any real-measured samples by which to compare the different types of training sets (the samples in this story are a part of my work, but simulated), but I do use a real-world set of test cases with the 29 nuclide mass training set. There are many challenges with doing this yet to be resolved, so it is not presented here in a research snapshot.

The lack of a feel-good resolution in this tale is not meant to reduce confidence in our national nuclear forensics capability or my research project, but rather to show how science does not necessarily result in clear-cut answers to questions. Much of the time, asking a question and answering it using the scientific method creates more questions than answers. For example, there are questions about why the gamma spectra approach gave such a wrong enrichment prediction (something echoed in my results, which are aggregate statistics of $450,000$ cases versus the one case presented here). Another question might be whether a 3-month or 6-month time since irradiation prediction error is too large of an error, or an acceptable error.

Author Commentary

Last, I wanted to make a short statement about my work on an even broader scale.

Every scientist should take note of the ethical and political implications of their work. Yes, I said it: science is political[9]! Although the morality of preventing or mitigating a nuclear disaster is not necessarily in question, the nuclear field (both commercial power and defense/the nuclear weapon program) is far from blameless when it comes to destroying human bodies and the environment. The mining industry caused uranium contamination and early death for many Diné in Navajo Nation and payouts/cleanup only began recently[10], plutonium production during World War II has resulted in the displacement and illness of US citizens around Hanford, WA, and government-sanctioned human radiation experiments were conducted on unwitting people and children. None of this (and so much more that's not mentioned here) comes as a surprise knowing the entire nuclear enterprise sits on a foundation of well-documented racism[11]. Last, the obvious must be stated: the US is the only country to ever deploy a nuclear weapon against another country, where the human toll was undeniably brutal[12]. This and much more is documented in a list of resources curated by Kalin Kiesling with help from the

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[9] Everyone knows it!

[10] For more information about the 500 abandoned mines and the cleanup efforts, read more here.

[11] Here's a good article on nuclear's racist roots.

[12] And Black American journalists exposed the government's lies about it

nuclear community[13].

None of this means that nuclear power as an energy source is inherently evil, but the industry and our government must acknowledge and take responsibility for abusing both the land and the beings on it. It is hard to hold this knowledge and still want to participate in nuclear science, but if more people in nuclear science and industry also hold this knowledge, then maybe taking life and land for granted can be less of a norm. Of course, better policy is always a stronger influence. Why am I saying all of this inside a(n unofficial) chapter in a nuclear engineering dissertation? Science is political, and so I must be too.

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[13] The resources are curated in this Google document.