Visualization of Nuclear Decay Activity for Forensics and Jurisprudence

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ABSTRACT
Visualization can play an important role in the successful prosecution of smugglers of interdicted nuclear materials. Nuclear forensics (the tracing of the source of interdicted materials) is grounded in the science of radioactive decay and those scientific databases which have been developed over the past century on nuclear materials properties. However in a court of law and when working with non-technical law enforcement officials, the process of nuclear isotope decay over time needs to be carefully explained. Most visual presentations of the decay process are static, and those few available dynamic visualization efforts are incomplete. This poster presents new methods for describing and visualizing the dynamics of radioactive decay which capture the radioisotope interaction between initial isotopic state (e.g. some fixed amount of Uranium or Plutonium) and subsequent daughter isotopes which appear and follow their own separate process of nuclear decay. As an example, temporal sequenced pie charts can vividly display quantitative decay amounts over time periods from months to millennia. Multiple approaches to visualize the radioactive decay process are presented and the advantages and disadvantages of each are discussed.

Keywords
Nuclear Forensics, Information Visualization.

INTRODUCTION
Nuclear forensics is the analysis of events of a nuclear nature which have international security implications. Illicit or explicit testing of nuclear devices (such as the recent North Korean underground bomb test) can be detected at a distance using seismological instruments or collection and analysis of airborne particulates. Nuclear forensics is an essential component of prevention and follow-up upon terrorist activities. The IAEA (International Atomic Energy Agency) has compiles incidents in their Illicit Trafficking Data Base (ITDB). According to the IAEA: "From January 1993 to December, 2012, a total of 2,331 incidents were reported to the ITDB/ Of the 2,331 confirmed incidents, 419 involved unauthorized possession and related criminal activities."

Given an incident of unauthorized possession and interdiction of nuclear material, follow-up analysis can be used to try to determine the origin and production source of the material. This can ideally be done by matching the results of radiochemical analysis (the "nuclear signature") against large libraries of already analyzed nuclear samples (Moody 2005).

However, in this case, nuclear forensics differs in one important aspect from traditional forensics—it has a temporal component based upon the mechanisms of radioactive decay. Consider, for example, if an individual's DNA changed over time according to a scientifically known formula and, at time of death, needed to be compared to a similar but different DNA sample collected at an earlier time. Fortunately this is not the case for DNA matching, but is very much a factor in nuclear signature matching (Nicolaou, 2006). For this reason, in a court of law, the process of radioactive decay must be carefully explained. It is our belief that proper visualizations of decay mechanisms and their quantitative changes over time will aid in this explanation.

Since nuclear material data is a digitized record of assays for component isotopes (Firestone, 1999) and elements, search of this data is complicated by the fact that radioactive atoms decay or morph constantly into atoms of different isotopes as the material decays. This morphing activity creates a new component for the same material. Therefore matching the original record is impossible against itself or any other nuclear material data unless the decay activity is built into the search algorithm. A nuclear material is composed of multiple radioactive isotopes. Therefore the decay visualization design must handle multiple events which can be confusing and difficult to comprehend unless the information is presented for optimal understanding.

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RELATED WORK

Scientific visualization has a vast literature which cannot be covered in the scope of this extended abstract. In addition there are numerous types of display for time series data, starting with line graphs and bar charts. Geotemporal displays, such as the Charles Joseph Minard's famous graph of Napoleon's disastrous invasion of Russia, while not the subject of this paper, may become pertinent to nuclear forensics when combining decay information with locations of nuclear reactors or uranium mines.

The traditional visual display of a nuclear decay chain is static, for example the following Figure 1 for the Thorium Series. The advantage of this visual display is that it captures a lot of information on the directed graph nature of the nuclear decay chain, as well as (inside each isotope sphere) the particular isotope of each radioactive element. What is missing is a feel for the dynamic mechanism of nuclear decay.

There is scant published work on visualization for nuclear decay. The work of Eller and colleagues (2006) is clearly oriented toward nuclear science and engineering professionals. Its interface begins with the two-dimensional isotope display below as in Figure 2, where the x axis is the atomic number and the y axis is the atomic weight. Eller's system allows for zooming in on any particular isotope and doing computations for irradiation periods on the elements. The system is clearly constructed for use by professionals in the field.

By contrast, the DCSERVIS tool (Azzam & Suksi, 2006) uses more traditional line graphs of decay activity over time as well as bar charts to show isotopic content. A series of bar charts are used for temporal display at particular time points (e.g. 30 days to 100 years) but it is difficult to shift between bar charts and the displays do not use uniform activity scaling on the y axis from chart to chart. Their work is limited to the decay series for U-238, U-235 and Th-232 series and their daughters rather that the full table of isotopes as captured in the Nuclear Wallet Card series (described below). DCSERVIS is grounded in numerical solution of the Bateman equations for radioactive decay products (Bateman, 1910).

DATA COLLECTION

Our main source of nuclear material data comes from Nuclear Wallet Cards(Tuli, 2011), a scientific database published by the National Nuclear Data Center at Brookhaven National Laboratory. It contains the latest nuclear physics facts for ground and isomeric states of all known nuclides. The radioactivity phenomena included in this database that are utilized for forensics include the atomic mass, atomic number, decay mode, branch percent of multiple decay products, half-life, natural abundance, and atomic weight. This scientific data serves as the basis for algorithms developed to formulate decay chains for the nuclide constituents of nuclear materials. The poster will describe the information contents of sample Wallet Cards.

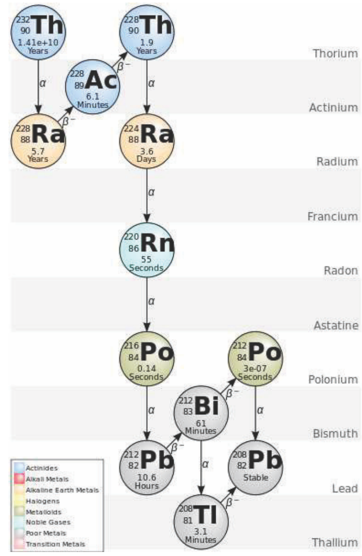

Figure 1. Thorium decay series

The fusion of scientific facts and dynamic computation produces a portrayal of a nuclear material as it changes form through time. This portrait serves as a signature for the material and can be produced dynamically for all radioactive constituents of a nuclear material sample by searching a data collection of evidentiary nuclear material artifacts.

KNOWLEDGE SYNTHESIS AND ISOTOPIC DECAY CALCULATION

Scientific principles applied via scientific rules from the Nuclear Wallet Cards results in forensics tool to reveal forms of the sample as a radioactive phenomenon. In this section we detail the time synthesized computation of the decay products proportion for standalone isotopes (original isotopes without interacting with daughter isotopes) and isotopes in a decay chain.

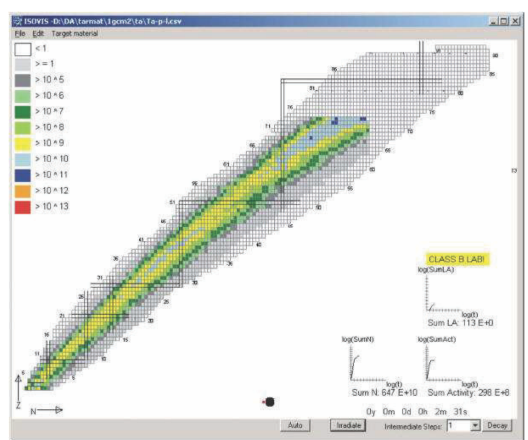

Figure 2: Two-dimensional isotope display

Standalone Isotopes

In some cases a legal team or jury needs to see how the radioactive isotopic constituents of a material change over time in regards to various decay rates. If a set initial amount is used as N0 at time zero for decay calculations at date intervals, a ratio can be computed to show what proportion or percent of the original isotope is left after decay. This exhibits rate of decay as a proportion rather than actual amount. It also provides information in regards to relative isotope constituents of a material. For a novice on a jury this proportional representation helps understand the state of a material and its properties if half-life computations are not a familiar part of their lives. The number 100 is used for the initial amount thus the decay amounts are also the percent of material left after decay. The poster will show how the materials transform over time.

Isotopes in a Decay Chain

Building on the calculation of standalone decays, we attempt to quantify isotopic proportion over time for any nuclear sample given its initial isotopic components. Using the Nuclear Wallet Cards, we can use the known half-lives of each isotope and the exponential decay formula f (t) = N = $N_0e^{-\lambda t}$ to predict the radioactive decay activity for the initial isotopes of this sample for the next one hundred years.

VISUALIZATION DESIGN MODULES

In this section we present multiple information visualization techniques for scientific visualization of the nuclear isotope decay process, including pie charts, circle packing, directed graphs, and line charts. The practical goal of this visualization process is to support nuclear forensics, the identification of the origin of intercepted smuggled nuclear materials.

Pie Chart

We can vividly display quantitative decay amounts over time periods from months to millennia using temporal sequenced pie charts. Our visualization process includes:

1. Calculate the amount of isotope left after given time (1 day, 30 days, 1 year, 10 years, 100 years, 1000 years) using a set initial amount of material (100 g).
2. Compute ratio: amount after time computation/initial amount.
3. Use ratio percent to create pie chart with the amount decayed taken out as a slice.
4. Display the results in a table with the time frames as columns and the pie charts listed under each isotope showing proportion would have decayed over time.

This display would be to show relative decay proportions so that a novice to the field could comprehend that some isotopes would last much longer than others given the radioactive decay process. It would also act as a visual signature for a type of material. Figure 3 shows examples of piechart visualization of quantitative decay amounts over time for isotopes Am-241and Cm-242.

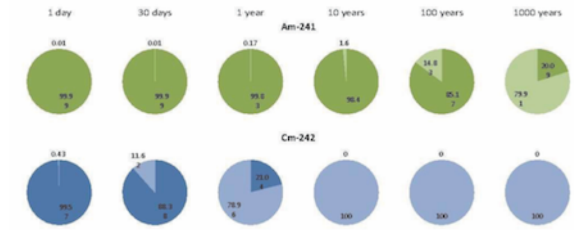

Figure 3: Piechart visualization of isotope decay

Circle Packing

Nuclear material isotope composition can be visualized using circle packing, a geometry where enclosure diagrams use containment to represent the hierarchy. In a Euclidean plane, the circle packing mechanism configures circles with a prescribed pattern of tangencies, yielding no two overlap circles in a contained boundary with most of the circles mutually tangent. The circle packing theorem is founded upon a rich body of classical geometries and we draw inspiration from Wang(2006) and Heer(2010) where circle packing was used to illustrate large datasets with hierarchies.

We visualize isotope composition of measured nuclear material assay taken from the Los Alamos National Laboratory (LANL)2 , which undertakes classified work towards the design of nuclear weapons and together with Lawrence Livermore National Laboratory (LLNL) are the two major laboratories doing such security nuclear forensics work to enhance the nation's defense. The nuclear material sample is analyzed by dividing it into aliquots which are subjected to isotopic specific tests. As seen in Figure 4, three samples measured on different dates are presented with unit circles. Within each circle are the sample's aliquots and various isotopes observed are displayed inside the aliquot circles. The area of the isotope circle is determined by the numerical value of weight percentage of that isotope within its element. For instance, aliquot A from sample ID Sep-10 consists of U-234 (2.5% U), U-235 (73% U), U-236 (16% U), U-238 (8.7% U), Pu-239 (94% Pu) and Pu-240 (5.8% Pu). The area of the corresponding circles is proportional to the element percentages. Accordingly, isotope circle with larger area suggests that the isotope is more abundant within the element.

Directed Graph

The decay events of a nuclear material can also be modeled as a directed graph where isotopes are represented by nodes and decay events from parent to daughter are represented by directed arcs. Modeling the decay activity as a directed graph allows for visualization of the process but also produces new information possible with graph analysis methods. The poster will also show directed-graph visualizations that show the result of decay-chain generation using data from the Nuclear Wallet Cards

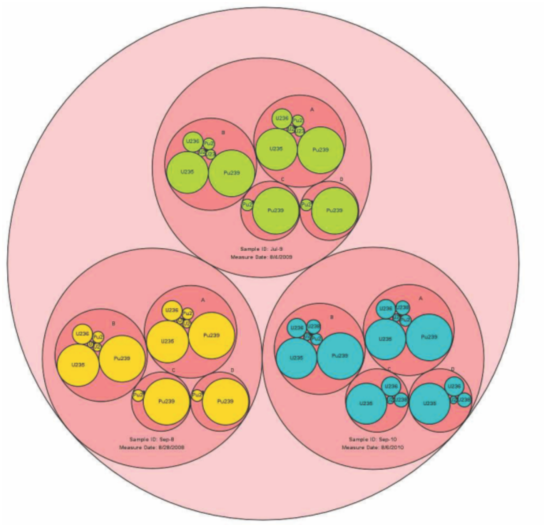

Figure 4: Circle Packing visualization.

database, which catalogues properties for ground and isomeric states of all known nuclides. The graph displays a composite of nuclear decay chains with root parents being the various isotopic assays recorded in the sample nuclear material. Those isotopes are Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, U-234, U-235, U-236, and U-238. Types of radioactive decay and isotope half-lives are highlighted on the graph. The directed-graph of networked decaying isotopes is built to illustrate the decay network until the isotopes reach a stable state at which they stop decaying.

Line Graph

Our direct goal is to predict the isotopic composition of our interested sample as a function of time. That would be the identifiable signature of the sample given the time domain. We may carry out a "snapshot" of the sample at any time T after the initial stage and store those snapshots in a digital library for future search purposes. A linear line chart can be produced to illustrate the visualization of sample evolution as proportions of radionuclide constituents. These line graphs will also be shown in the poster session.

DISCUSSION

We have presented visualization of radioactivity decay of nuclear samples in more than one format. We visualize the proportion of decay products as linear and circular motifs, the decay chain as directed graph, and isotopic composition of nuclear sample as circle-packing diagram. There are advantages and disadvantages of these charts. The selection of a visual style is driven by the information sharing purpose. In the case of nuclear scientists the style is most usually the directed graph and line graph showing sequential decay products and amounts and covers the quantitative information familiar to them. However, in the case non-scientific people on a jury or in the field, more generalized meaning can be represented with pie and circle-packing charts.

ACKNOWLEDGEMENTS

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