Learning by Being: A Human-Powered Ping-Pong Ball Nuclear Reactor

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1. INTRODUCTION

Learning can be both fun and effective when a complex concept is distilled to a laughably simple analog. If sufficiently silly, the analog will lend itself to repeated discussion in follow-up conversations, propagating its educational value well beyond the initial presentation. Another effective tool is experiential learning, about which much has been written elsewhere. The combination of these two – i.e., a laughably simple experiential analog – can be potent.

In this paper an experiential analog for the fundamental chain-reaction process of a nuclear fission reactor is described, using human participants, ping-pong balls, and a simple set of rules. The analog lends itself readily to classroom demonstration as it makes use of the two-dimensional array of students typically found in classroom layouts, and it involves very little setup time so multiple repetitions (trying out different assumptions and rules) are possible. Both an advantage and a disadvantage of the analog is the delight that most people (of any age, but particularly younger) derive from throwing ping-pong balls around a room, or at each other.

2. NUCLEAR FISSION

Nuclear fission (or typically just “fission”) is the process that generates the heat in a nuclear reactor, typically involving atoms of uranium. Fission was discovered in 1939 and, given global events of the day, was almost immediately put to use for military purposes in the development of the atomic bomb (deployed over six years later at Hiroshima and Nagasaki, Japan). Simultaneously, its potential was recognized as both a valuable scientific tool and a source of almost limitless energy (Leo Szilard, the Hungarian scientist who famously conceived the fission chain reaction while contemplating the pattern of traffic lights at an intersection in London, applied for three patents during WWII years: two for nuclear reactor and one for a new weapon). However, these peaceful applications had to wait for the post-war years before being developed.

Today nuclear fission is at the heart of over 400 electricity-generating power plants around the world, as well as numerous aircraft carriers and submarines in several navies. It is also used to produce neutrons in “research reactors” operating in most technically advanced nations, used principally in the development of advanced materials, ensuring the safety of critical aerospace, nuclear, and other components, and in the production of radioisotopes for medicine and industry.

Nuclear fission is the splitting of atoms (the word “fission” was borrowed from the world of biology, where it applies to cell division). All stable or very long-lived radioactive atoms represent a sort of “stalemate” between two powerful and fundamental forces of nature: the so-called Strong Nuclear Force (SNF) is the glue that binds all nucleons (protons and neutrons) together, and the Electromagnetic Force (EMF) is the force that tends to repulse similar electric charges (such as the positively-charged protons) from each other. As its name implies, the Strong Nuclear Force is quite powerful; however it is only effective over the relatively short distances found in the nucleus of atoms. EMF, on the other hand, retains its effectiveness over much larger distances (up to several metres). All nuclei are therefore hosts to a nano-scale tug of war between these two forces, and as we look at larger and larger nuclei further down the Periodic Table, we see the SNF – although the stronger of the two at short distances – gradually losing its advantage over the EMF.

Nature regains some ground by adding more and more neutrons to the mix as nuclei get larger, since each extra neutron brings with it more SNF, but zero EMF (since it has no electric charge). Thus, lighter nuclei tend to have even numbers of protons and neutrons, but once you get over 50 nucleons we start to see a steadily increasing ratio of neutrons to protons. Also around this 50-nucleon threshold we begin to see nuclei requiring more and more energy expenditure to keep their structure intact; it is, in other words, energetically favourable for them to break apart into smaller nuclei. The reason they don't all spontaneously do this is due to the iron grip that the SNF retains on each of the nucleons at close quarters, as long as more and more neutrons can be added to the mix.

The inevitable end of this tug-of-war, and end of the the dominance of the SNF over the EMF, occurs once the total number of nucleons gets over 230. This brings us to uranium, with typically 238 nucleons (U-238), including 92 protons and 146 neutrons. The trace constituent (0.72%) U-235 has 92 protons and only 143 neutrons. Uranium exists at the edge of the naturally-occurring world: no heavier atom exists in nature, although many have been created artificially since the 1930s.

Uranium itself is not stable. Both of the naturally-occurring uranium isotopes will shed mass regularly by ejecting alpha particles, consisting of two protons and two neutrons (basically helium nuclei). This is not a massive stampede from the brink: on average it takes 4.5 billion years for half of any amount of uranium to disappear this way, and this period of time is known as uranium's "half-life". For all practical purposes uranium is therefore effectively stable, although disappearing at rate of XX% every hour. The loss of an alpha particle turns the uranium nucleus into a thorium nucleus, which itself is unstable and decays with similar lethargy (half-life XXX years) to radium. This "decay chain" continues down through the Periodic Table, until stable lead is reached. Since the age of the Earth is approximately equal to one half-life of uranium (4.5 billion years), approximately half the planet's total uranium inventory has disappeared over its lifetime, leaving behind a legacy of decay products that account for a good fraction of the natural background radioactivity in our rocks and soil.

This much was well-known by the 1930s, but what scientists didn't realize until some unexpected results from uranium-neutron reactions showed up, was that uranium can also be made to jump directly past lead to nuclei roughly half the size of uranium: the uranium nucleus could be split. Doing this requires a small nudge of energy, achieved by making uranium slightly heavier; i.e., pushing uranium past the brink of naturally-occurring elements. If a single neutron is added to a uranium nucleus it can be the "last straw", so to speak, and cause the uranium nucleus to agitate and then break apart roughly in half. Sometimes the agitation will not be as violent and the heavier uranium nucleus will instead resolve its sudden SNF/EMF imbalance by converting protons to neutrons – turning first into neptunium and, shortly afterwards, plutonium. Both of these elements do not exist naturally on earth.

It turns out that the minor constituent of uranium, U-235, is closer to the brink than its more abundant brethren U-238, and in fact close enough that this "last straw" can be introduced by simply adding a neutron, without any additional injection of energy. U-238, on the other hand, is marginally more stable and requires a neutron with a minimum kinetic energy of about 1 million electron-Volts (1 MeV). This is, in fact, part of the reason why U-235 has such lower natural abundance than U-238.

From the point of view of practical applications, the most important aspect of fission is not that a nuclei can be split, but that a great deal of energy is released in the process, along with a small number (two or three) free neutrons. Both emissions stem from the fact, as discussed above, that heavier nuclei like uranium need a lot more energy and extra neutrons to hold them together, compared to lighter nuclei. Following a fission event, therefore, one is left with two fragments that have many more neutrons and far more energy than they need. Almost immediately upon splitting a good portion of this excess energy is liberated, along with two or three of the suddenly unnecessary neutrons. Most of the released energy manifests itself in the kinetic energy of the two fission fragments themselves, flying apart from each other until they slow down the matrix of surrounding uranium atoms, converting their kinetic energy to heat. Some of the energy shows up as gamma rays, and some shows up in the kinetic energy of the two or three released neutrons.

The released neutrons are what caught the eye of scientists shortly after fission was discovered, for they enable the whole fission process to be initiated in surrounding uranium nuclei. Since each fission event releases two or three free neutrons, a practical “chain reaction” is possible since one is allowed, besides the one neutron needed to propagate the chain, one or two other neutrons that can be absorbed either parasitically in the reactor core’s internal structure (without further use), or in absorber control elements that can be used to control the rate of the chain reaction. In a nuclear reactor these control elements are typically made of material like cadmium that absorbs neutrons voraciously. Increasing or decreasing the amount of this absorber material in the core at any time (e.g. raising or lowering control rods), changes the number of neutrons that get absorbed, and this affects the overall power level of the core.

To increase the probability of the released neutrons encountering and causing fission in a neighbouring uranium nucleus, they must first be slowed down to a manageable speed. When first released they have kinetic energy in the range of 1 MeV, corresponding to a speed of about 0.1c, or 10% the speed of light. To be useful they must be slowed down as much as possible, for the same reason that it is easier to catch a slowly-lobbed baseball than one thrown at 97 mph. If the neutrons are allowed to bounce around in a hydrogenous material like water, the neutrons will lose energy in multiple collisions with hydrogen nuclei, and this material is called a “moderator”. Eventually the neutrons will reach an energy level corresponding to the thermal energy of the moderator material itself (i.e. the vibrational energy of the molecules), and can be slowed down no further. At this energy level (typically less than 1 eV) the neutrons are referred to as “thermal” neutrons, with speeds in the range of 2 km/s. Reactors that moderate neutrons in the fashion are referred to as “thermal reactors”, to distinguish them from reactors that make use of fast neutrons only (e.g. “fast breeder reactors”).

3. PING-PONG BALL REACTOR: OPERATION

With the ping-pong ball reactor, students can take on the role of uranium fuel, spaced apart within a moderating medium. The neutrons of this reactor are ping-pong balls. Some idea of the scale of the nuclear world can be gained by comparing the size of these ping-pong balls to actual neutrons: if a neutron were to be magnified to the size of a ping-pong ball, then the corresponding uranium nucleus would be about the size of a full-size soccer ball, and the neighbouring uranium nuclei (assuming uranium metal) would be over six km away in all directions! The “soccer ball” nucleus would thus sit in the centre of over 1700 cubic km of essentially empty space (occupied only by a rarefied electron cloud), and this forms the “target” that free neutrons must hit – without any long-range attractive force (e.g. EMF) to assist.

With the ping-pong ball reactor we cannot mimic this actual distance between uranium nuclei, but the information is interesting nonetheless. In fact, although students will be holding and releasing “neutrons” much as uranium nuclei would, it is probably better to pretend that each student represents a more macroscopic entity, such as a fuel bundle of uranium, since this lends itself more readily to the analog if standing/sitting in a regular matrix, and to analogs of neutron moderation and reflection that are discussed below.

The rules of setup and operation are quite simple:

1. Arrange a number of students (minimum about 16) into a regular lattice (e.g. minimum 4x4), and give each student two ping-pong balls apiece.

2. Students are told that if a flying ping-pong ball happens to hit them anywhere on their body, their reaction should be to toss their two ping pong balls up into the air, without any particular target.

3. An “initiating” ping-pong ball is tossed into the middle of the matrix of students, to get things going.

Depending on the number of students, their reaction time, the height of their tossed ping-pong balls, etc, a chain reaction should ensue and last for a relatively short time. Methods for increasing this propagation time involve improvements in efficiency that quite often are directly comparable to what reactor designers come up with in order to increase the efficiency of real nuclear reactors, and this is where the educational value of the human-powered ping-pong ball reactor really lies, as discussed in the next section.

4. PING-PONG BALL REACTOR: LESSONS

Once the “shake-down” initial run of the human-powered ping-pong ball reactor is out of the way, the real educational value of this experiential analog comes into play. Students and teachers will easily come up with several suggestions for improving the chain reaction, and most of these methods reflect methods that reactor designers and operators actually use in the design or operation of real nuclear reactors.

Some of these methods are listed in the following table, with commentary on their significance to reactor design and operation.

Variation	Significance
number of ping-pong balls per student	Uranium fission releases two or three neutrons. Varying the number of ping-pong balls per student demonstrates the effect of neutron number on the rate at which the chain reaction propagates. One ping-pong ball per student should be quite uneventful. Three or four per student should be quite interesting. Estimate the number of balls flying through the air at any on time – with one ping-pong ball per student this number should always by one; i.e. there is no multiplication. As you increase the number of ping-pong balls per student the multiplication should increase. This demonstrates why reactors would not work if fission released only one neutron per event.
shape of student matrix	Reactors are most efficient when their surface-to-volume area is minimized, which minimizes leakage of neutrons from the core (into surrounding shielding). The most efficient shape for a reactor would therefore be a sphere; however, engineering limitations typically lead to cylinders instead, and thus most large reactors are cylindrical. This effect will be noticed readily if the students are re-arranged into a straight line.

number of students	Reactors use an amount of fuel that provides the total desired power output, but also which makes most efficient use of neutrons. Keeping shape of the matrix constant but changing the size will keep the chain reaction going longer since “leakage” out to the sides is reduced. The effect on overall “power production”, indicated by the number of ping-pong balls in play at any on time, may not be demonstrated so readily since the chain reaction will tend to die out where it started, and spread over the matrix. The “multiple toss” variation below partially addresses this limitation.
spacing of students	An important early parameter in the design process for nuclear reactors is the spacing of the fuel. Increased moderator volume between fuel channels leads to slower rate of change to the chain reaction, since neutrons have further to go and take longer to slow down. This can play an important role in the control design of the reactor, since it slower dynamics lead to simpler design requirements for control and safety systems. In the ping-ball reactor there is no moderator (although friction will slow the ping-pong balls down a certain extent), but the distance will affect a change of rate due simply to time-of-flight changes.
multiple toss per student	In an actual reactor there are trillions and trillions of uranium atoms per cubic cm, leading to a fairly constant level of fission activity throughout the reactor (except where edge effects lead to a marked decrease in activity near the borders). In the ping-pong ball reactor the local activity should die quickly since student distribution is, in comparison, very sparse and each one only has one toss. This can be modified by either giving students extra ping-pong balls to keep in their pockets, to be pulled out and used once their first pair have been tossed. This “recharging” doesn’t have a direct analog to real reactors, although it partially mimics the significantly higher density of a real fuel matrix.
delay in throwing	Some “fission products” (the two parts of the uranium nucleus) are spontaneous neutron emitters. These neutrons will be added to the population of neutrons in the reactor released directly by the fission events, but at a much slower time constant ranging from seconds to many hours). Reactors are typically designed such that these extra neutrons are necessary for the propagation of the chain reaction, which has the effect of reducing the overall time-constant for the chain reaction. Changes in the fission rate thus occur on a slower time-constant, which (like the larger/slower moderator) leads to simpler design requirements for control and safety systems.
use of reflection	Reactors are designed with an efficient neutron scattering material (water, beryllium, etc.) surrounding the core, in order to return escaping neutrons back to the fission chain reaction. It will quickly become apparent with the ping-pong ball reactor that “leakage” plays an important role in bringing the reaction to a halt, particularly if less efficient shapes of the matrix are used. If the students could be surrounded on all sides by walls, or at least two sides (such as placing them in the corner of the room), it is possible to demonstrate this effect of reflection; i.e., the students on the outer edge of the matrix next to the walls should find that the ping-pong balls they toss have a better chance of hitting other students.

some students designated “catchers”	Reactors are full of material that absorbs neutrons either parasitically (no net benefit), or as a function of control design (e.g. control rods). One of the key goals of efficient reactor design is to minimize this material as much as possible, while maintaining sufficient control capability. If a reasonably well-performing ping-pong reactor is achieved (perhaps after employing some of the efficiency improvements mentioned above), an extra variation worth trying is to ask certain students to be “catchers” (absorbers) instead. In other words, their job is to grab ping-pong balls that stray near them, removing them from the chain reaction. If the ping-pong ball reactor is relatively inefficient to begin with this added effect may not be noticed, but otherwise it is worth trying since it demonstrates a key aspect of reactor control.
basic rule changed: now must *catch* a ping-pong ball first, before tossing own ping-pong balls	In an actual fission reaction, each uranium nucleus must first “catch” an incident neutron, which is a different concept than what is portrayed by the usual simplification of a neutron “hitting” a uranium nucleus. The fact that a uranium nucleus must first “catch” a neutron means that slower neutrons are more likely to cause fission than fast neutrons, and hence the need for a moderator. This is a simple method, therefore, for demonstrating the role of a moderator, which is not usually an intuitive concept since one normally associates faster collisions with more likelihood of energetic results. As a “thought experiment” extension, ask the students how one might increase the probability of the ping-pong balls being caught – the answer, of course, is to slow them down somehow. As a further thought experiment, propose the idea of everyone standing up to their waist in a swimming pool, and doing the same experiment – now the ping-pong balls are bobbing by, barely moving beyond the random movement of the water surface. This is very much an analog to neutrons being slowed down (technically referred to as neutron *moderation*) to increase the probability of capture – and water was used to achieve this…
no more “thought experiment” – let’s moderate!	If the rule is changed to catch-first (see above), and all manner of “catching” is allowed (including retrieving rolling ping pong balls off the floor), then neutron slowing-down, or *moderation*, can be easily demonstrated – particularly if students are positioned close enough to the floor (e.g. on their knees, sitting on the floor, or even sitting in their seats). In effect, the floor is “moderating” the ping pong balls, and, in direct analogy to a nuclear reactor, the human chain reaction will continue for a several minutes, or even in perpetuity if there is sufficient “reflection” of stray balls back into the “core”. This is because students are much more able to catch the balls when they are slowed down, just like uranium catching neutrons .

4. HAVE FUN!

The basic framework has been outlined here for fun and hopefully not-too-chaotic experiential learning exercise that provides an analog to nuclear reactor operation. Students and teachers are encouraged to try new ideas and improvements. The Canadian Nuclear Society is a not-for-profit organization of individuals dedicated to improved communication of nuclear topics – with students, the public, the media, and within the nuclear industry. We would love to hear about your experiences with your own ping-pong ball nuclear reactors (good and bad!). Please contact Dr. Jeremy Whitlock by email (address at top of paper) with your stories and suggestions.