A Simple Neutron-Physics Game to Assist Conceptual Learning of Nuclear Engineering

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INTRODUCTION

Engineering learning and teaching styles are known to be somewhat contradictory [1]. While many students tend to prefer active and visual learning, most education is in the form of abstract and sequential concepts. This approach is no different in nuclear engineering, where core concepts include difficult and demanding subjects such as energy and direction-dependent neutron transport.

Computer games provide a fun and natural way to reinforce learning and gain valuable intuition for physical phenomena. In this vein, an open-source, neutron-physics simulation game was created [2] that allows users to explore interactions of neutrons with different materials and geometric configurations. Basic concepts such as scattering, absorption, fission are exposed to students in an interactive, composable environment. Used in conjunction with traditional teaching methods, such a tool may prove valuable in an effort to instill basic physical intuition and accelerate the learning of such complicated subject matter.

METHODOLOGY

The neutron-physics game is a time-step based Monte Carlo simulation [3]. On each time step of the simulation, neutron positions are updated as a function of their velocities. Then, if the neutron is inside any material, possible reactions (e.g. fission, scattering, etc.) occur according to probabilities defined by that material. These probabilities are calculated as a function of distance each neutron traveled on the current time step. Interaction probabilities and value sampling are not necessarily done using "correct" nuclear data or equations. Rather, fundamental concepts are approximately modeled and specific values for reaction probabilities were adjusted to make playing simulation informative and fun. Physics concepts modeled include:

- Absorption: The probability of absorption is a function of neutron energy/speed. Absorber material can also be burned up over time.
- Scattering: All scattering is isotropic.
- Fission: The probability of fission is a function of neutron energy/speed. Fuel material can also be burned up over time, losing reactivity. The number of neutrons released from a fission event is randomly sampled from a normal distribution to be some integer near 2.
- Moderation: Neutrons can lose some portion of their energy when scattering in certain materials. Some materials moderate more or less effectively as a function of their "temperature" (number of neutrons inside them) - this enables crude modeling of concepts like reactor void coefficients.

In addition to the neutron population, the positions of materials and other blocks are tracked and drawn to the screen in real-time. The user can drag around material blocks with the mouse. Partially transparent detector blocks can also be moved around by the user to investigate neutron populations of specific parts of the simulation environment. The user can also introduce isotropic bursts of neutrons at any location they right-click in the environment (including inside material blocks). If materials are moved on top of each other, the one on top "wins" and becomes the sole determiner of physics for that region of the simulation.

There are many improvements and features waiting to be added. One limitation involves how time steps are calculated. Because the simulation operates with a variable frame rate, the time change and position change for neutrons between time steps increases as the system becomes more computationally expensive to model. This slowdown results in neutrons traveling too far between events and reaction probabilities being scaled inappropriately high. This could be prevented by adjusting a neutron weight parameter instead of increasing the neutron population when the time change between time steps grows too large. This and many other improvements are possible.

EXPERIMENTS AND RESULTS

Below, three simple experiments are presented that show how this simulation game can be used to explore nuclear engineering principles. Because the project is open source, you can download and run these and other experiments yourself. The code is available on Github at `https://github.com/rwcarlsen/reactor`. Materials and other objects used in the simulation experiments below are represented by different colored squares. The meaning of each square is as follows:

- White (large): neutron energy independent scattering medium.
- Green (medium): neutron energy independent moderating/scattering medium.
- Blue (medium): neutron energy dependent burnable absorber.
- Purple (small): fissile material or fuel.
- Olive (small): togglable constant streaming neutron source.
- Yellow (transparent): neutron detector that reports the number of neutrons inside it without affecting neutrons or material properties underneath itself.

Attenuation

A classic initial problem in nuclear physics involves the attenuation of particles through materials. This simple concept becomes more complicated when considering changes in absorber atom density as neutrons are captured. These concepts can be easily demonstrated using the neutron physics game. An attenuation experiment setup is shown in Figure 1. It is comprised of a unidirectional-beam neutron source, detector, absorbing material, and an additional detector. The initial detector provides an unattenuated neutron count/density. The neutrons then interact with the absorbing material over the width of the block. The final detector provides an attenuated neutron count/density.

After the beam is turned on, active attenuation of the neutron beam can be observed as shown in Figure 2. In time, however, the absorber atoms gradually become transmuted and cannot capture additional neutrons. Eventually, the material becomes effectively transparent to neutrons, as shown in Figure 3. Upon completion of this particular experiment, the entirety of the absorber material in the beam's pathway has been burned. This phenomenon is shown clearly in Figure 4 with the burned portion in grey and the unburned portion in blue.

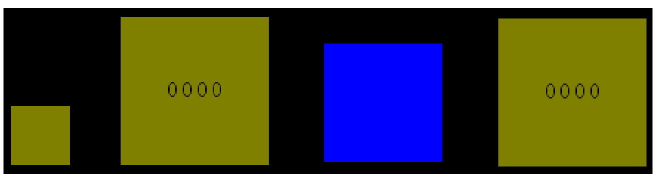

Fig. 1. An attenuation-with-absorption experimental setup.

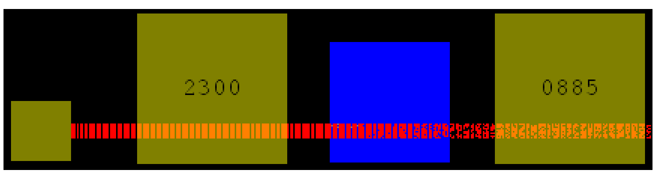

Fig. 2. Initially, attenuation is shown due to neutron absorption.

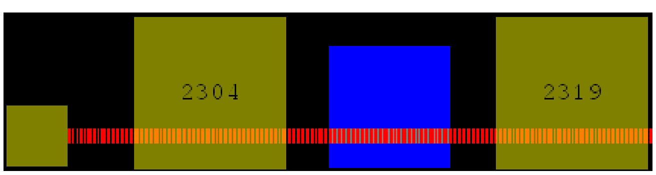

Fig. 3. Upon depletion of the absorber, no attenuation of neutrons is observed.

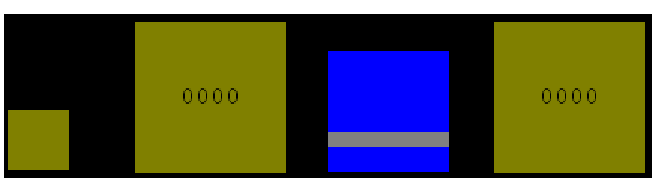

Fig. 4. After turning off the neutron beam, absorber depletion is observable.

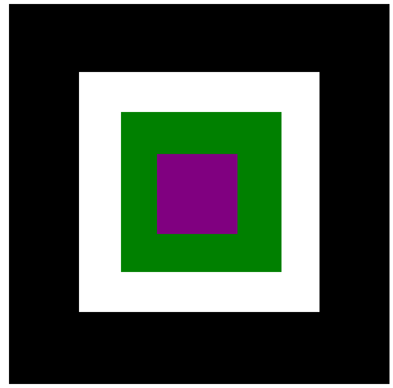

Fig. 5. Super-critical thermal reactor setup.

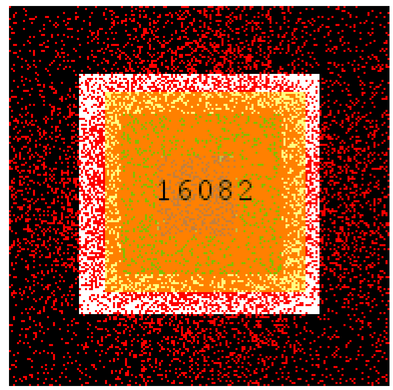

Fig. 6. Super-critical thermal reactor continues to grow its neutron population.

Super-criticality and Burnup

The configuration shown in Figure 5 contains a fuel block surrounded by a region of moderator all enclosed by a scattering block that acts as a reflector. After a single burst of 1,000 neutrons is released into the center of the fuel, the neutron population quickly grows. With a detector placed over the top of the super-critical system, the neutron population growth can be quantified. After just over 2 minutes, the population passes 15,000 neutrons as can be seen in Figure 6. This growth would continue indefinitely if it weren't for the depletion of the fuel.

After a few minutes of operation in the super-critical state, the reactor was shut down by removing the fuel from the system until the neutrons died away. This reactor configuration results in non-uniform burnup of the fuel. This is apparent in the post-shutdown state shown in Figure 7; the fuel's purple color transitions to grey as fissile atoms are burned up. The fuel nearer to the moderator has higher burnup due to the short mean free path of thermalized neutrons coming from the moderator. Also notable is that removing the moderator from this configuration would result in a sub-critical configuration.

Sub-critical Multiplication

Sub-critical multiplication is an interesting phenomenon that can be illustrated well in the game. To show this, we break the experiment into two setups: a neutron source streaming

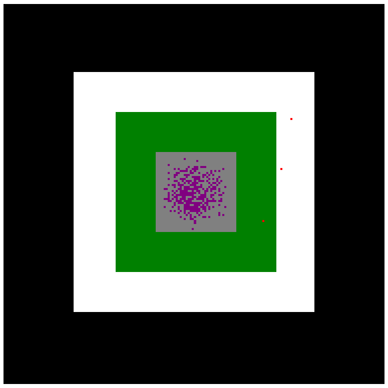

Fig. 7. After shutdown, the thermal reactor exhibits non-uniform burnup in the fuel.

Fig. 8. Reference setup for measuring neutron equilibrium in a scattering medium.

into a non-fuel environment, and a neutron source streaming into an environment with fuel. Figure 8 shows the unfueled environment with the neutron streaming source on the right and a large scattering block on the left. A detector is placed over the scattering medium and the streaming source is turned on. Figure 9 shows this setup after the detector has reached an approximate equilibrium state with about 2,500 neutrons.

The setup and procedure show by Figures 8 and 9 is repeated with a fuel block placed in the center of the scattering medium - shown in Figure 10. After turning on the neutron source, this setup reaches an approximate equilibrium state with about 10,000 neutrons - nearly four times more than the same setup without the fuel material block.

CONCLUSIONS

A new tool has been provided to assist the early learning of both simple and complex concepts in the field of nuclear engineering. The game allows users to compose a neutron-physics scenario and observe complicated interactions such as scattering, absorption, and fission. Users are provided the capability of constructing scenarios with multi-directional neutron beams, isotropic neutron pulses, and detectors.

A number of features can be developed to enhance the learning capacity the game provides. For example, materials

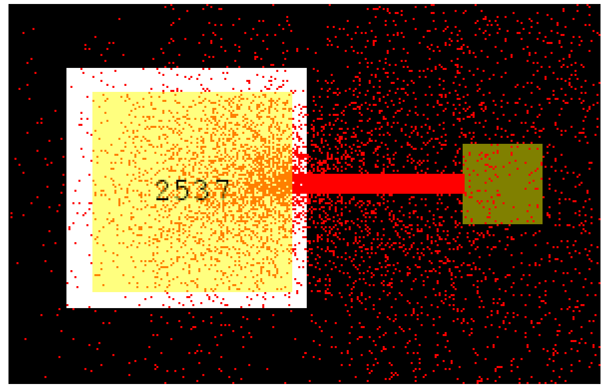

Fig. 9. Reference scattering setup reaches an equilibrium neutron population of about 2500 neutrons when fed by a constant streaming source.

Fig. 10. Fuel was introduced into the scattering medium creating a sub-critical multiplication configuration.

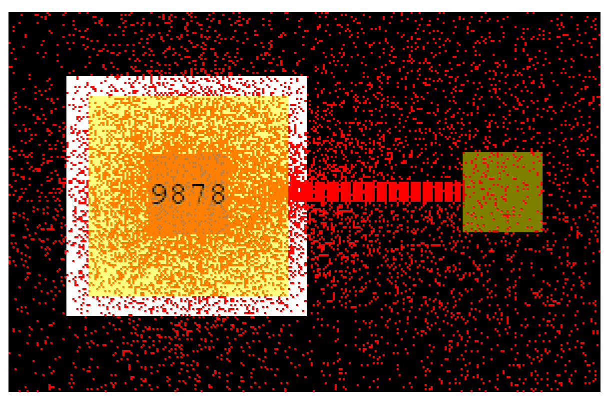

Fig. 11. Sub-critical multiplication reaches an equilibrium neutron population of about 10,000 neutrons when fed by a constant neutron source.

could be introduced that include multiple reaction events, such as absorption and scattering. Further improvements might include the ability for users to compose their own objects on the fly to investigate the effect of cross section magnitudes, in both an absolute and relative context.

The tool's purpose is to provide a basic platform upon which these complicated interactions can be visualized and intuition can be built. As noted by Felder [1], such tools can fill a niche not normally provided to engineering students. Used in conjunction with traditional teaching methods, a tool such as this may prove to be quite useful in real-life educational settings. The authors welcome critiques, comments, feedback, and requests through either personal communication or through interaction with the Github repository.

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