Neutrino Detectors and Neural Networks for Nuclear Nonproliferation

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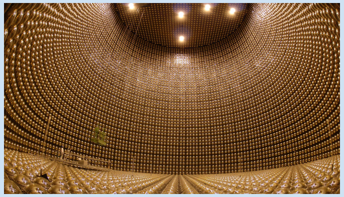
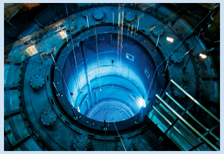
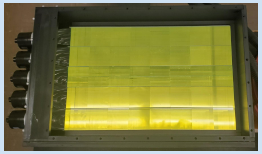
Introduction



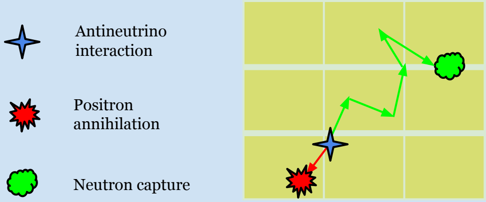
Super Kamiokande Neutrino Detector- Gifu, Japan

Neutrinos are weakly interacting particles, so most neutrino detectors are massive apparatuses buried deep underground to shield from background radiation.



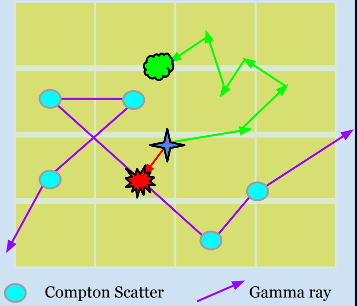


The MiniCHANDLER detector, however, can measure the neutrino spectrum of a nuclear reactor without any shielding from cosmic rays and is small enough to be transported in an ordinary trailer. Because the neutrino spectrum of civilian energy production differs from that of plutonium breeding for weapons, future iterations of this detector could be the future of nonproliferation monitoring.



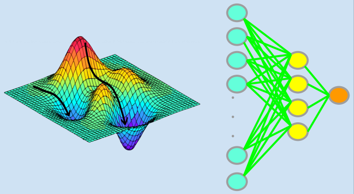
MiniCHANDLER is a 3-dimensional layered detector which vertically alternates between a lattice of plastic scintillator cubes and a thin neutron capture sheet. The plastic cubes emit a short pulse of light in response to energetic charged particles, and the sheets emit a long pulse of light in response to neutron captures. This light is then channeled to photomultiplier tubes by total internal reflection. When an electron antineutrino from a reactor strikes a hydrogen nucleus, it produces a positron and a neutron in an interaction called inverse beta decay (IBD). This leaves a distinctive short pulse-long pulse signature that distinguishes the neutrinos from most background events. Unfortunately, cosmic ray neutrons can mimic this signature by scattering protons, producing short pulses, and then capturing, producing a long pulse.

Neural Network Use Case



- **A way to distinguish IBDs is needed**

The positron produced by an IBD annihilates with an electron, producing two back-to-back gamma rays that create more short pulses by scattering electrons. If an algorithm can learn to recognize the pattern left by this Compton scattering, the problematic neutrons can be weeded out.

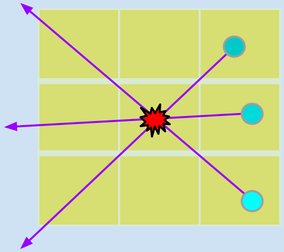


- **A shallow neural network was trained with a computer simulation of the planned CHANDLER detector.**

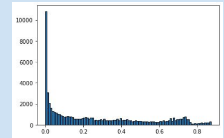
The energy deposition data was processed into key defining variables, including the distance between the neutron and positron hits, the total Compton scatter energy, and 23 others. The network achieved a significance of 146 compared to the previously used decision tree that achieved 130.

- *Significance correlates to how quickly an analysis would detect a change in reactor operation.*

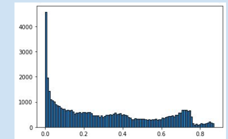
Escape Score



Neutron Escape Score



IBD Escape Score



- **Events where one of the gammas escapes are difficult to classify.**

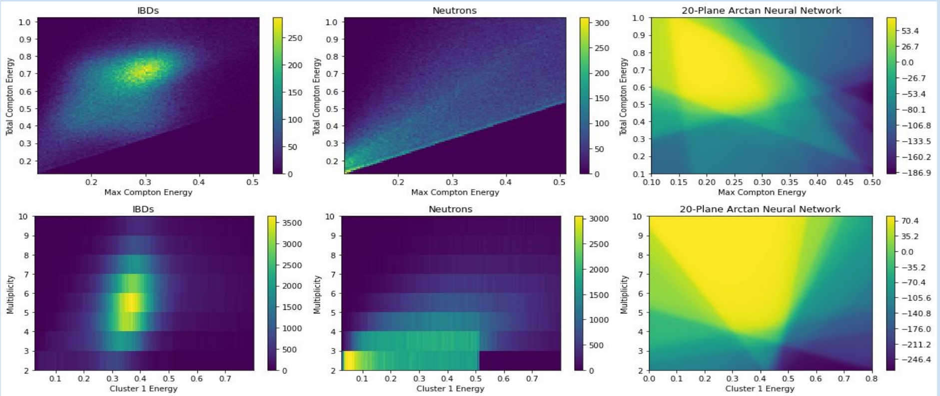
To better identify these events, the probability that the missing gamma could have escaped the detector was calculated. A cut in this variable improved the signal/noise ratio by 20%.

Reward Optimization

- **The aforementioned network trained to maximize accuracy, which is not an ideal metric in high-noise environments.**

To improve the network and speed up training, a reward function that directly reinforces an increase in significance was implemented. This improved the significance to 160, outperforming all other classifiers.

Neural Network Histograms



The network draws visually intuitive classification boundaries in the data through the combination of many linear hyperplanes. Unlike many modern neural networks, this is not a black box algorithm.

Acknowledgements

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References

[1] Alireza Haghighat, Patrick Huber, Shengchao Li, Jonathan M. Link, Camillo Mariani, Jaewon Park, and Tulasi Subedi, "Observation of Reactor Antineutrinos with a Rapidly-Deployable Surface-Level Detector," Physical Review Applied 13, no. 3 (March 11, 2020): 034028. https://doi.org/10.1103/PhysRevApplied.13.034028.

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Images

Super Kamiokande- https://www-sk.icrr.u-tokyo.ac.jp/en/sk/assets/experience/gallery/img/photo/pr_photo_66.jpg

Nuclear reactor- https://www.linquip.com/blog/wp-content/uploads/2021/02/nuclear-reactor-4.jpg

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MiniCHANDLER- Keegan Walkup