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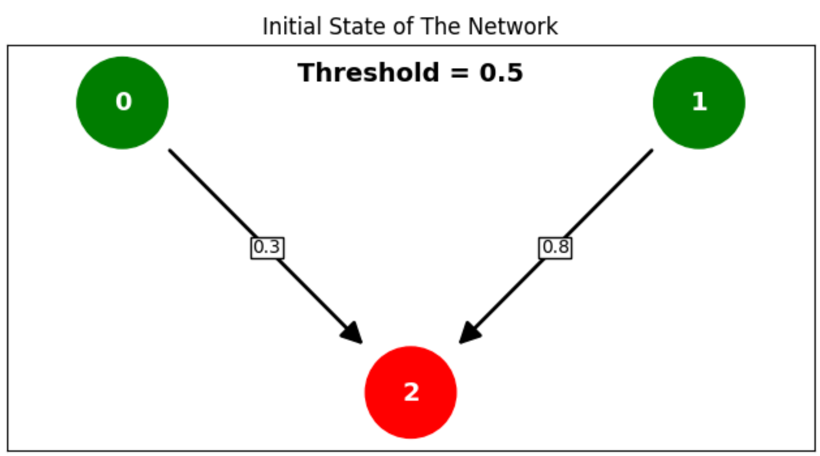
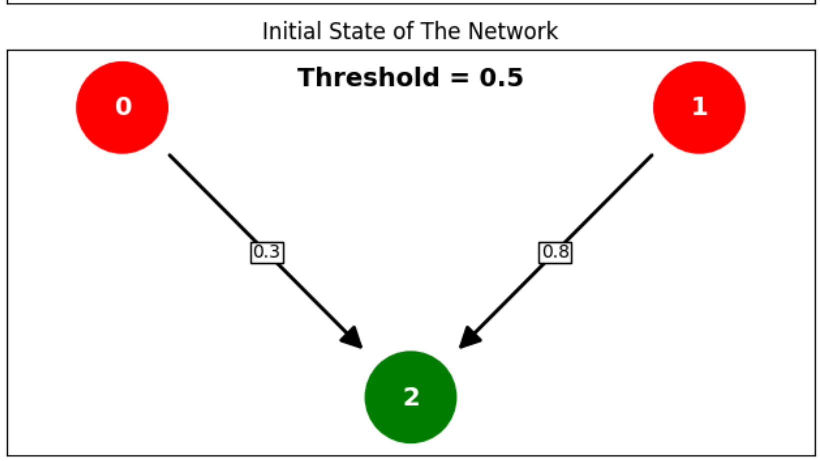
Summer 2025 End of FURSCA Report

Topological Relations Between Artificial Neural Networks and Information Theory

My project focused primarily on coding artificial neural networks (ANNs) of various sizes using Python and applying concepts from information theory to analyze how network structure contributes to information flow. The goal of the project was to identify precisely what influences total information and to develop methods to break down large networks into smaller ones without significantly losing information.



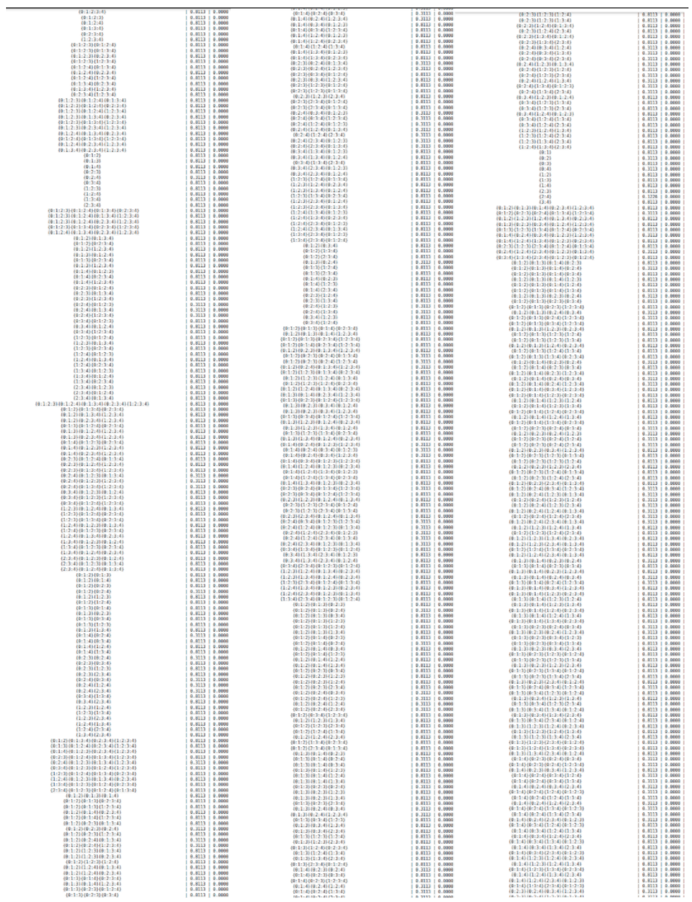


In an artificial neural network, there are many different components. As shown in the figures to the right, the network includes circles labeled numerically. These circles represent nodes that can either be green (activated) or red (deactivated). When a node is activated, it serves as a source of information, sending signals through connections represented by arrows. The strength of each connection is shown by the number in the arrow. Initially, the activated nodes are chosen randomly. To determine if a node will still be activated, each node will "look" at the connections coming into it, and then add all of the active incoming connections together and compare the total to a threshold value. If the sum exceeds the threshold, the node becomes activated; otherwise, it becomes deactivated.

The second part of my project is then applying Information theory to the results of different artificial neural networks. Information is made up of three main categories of information:

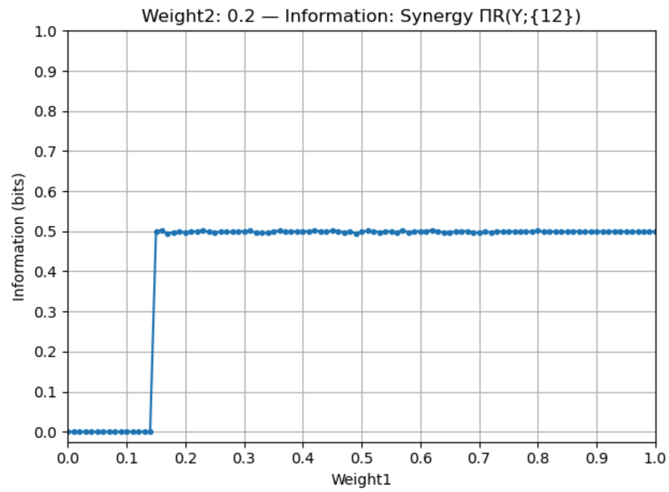
- **Unique Information**: Information exclusively provided by a single source.
- **Redundant Information**: Information provided by multiple sources at the same time, effectively repeating the same information.
- **Synergistic Information**: Emergent information not explicitly stated by any single source but collectively comes together from multiple sources. A helpful analogy for synergistic information is a puzzle, where each piece offers unique information, but the full picture (synergistic information) only emerges when all pieces are combined.

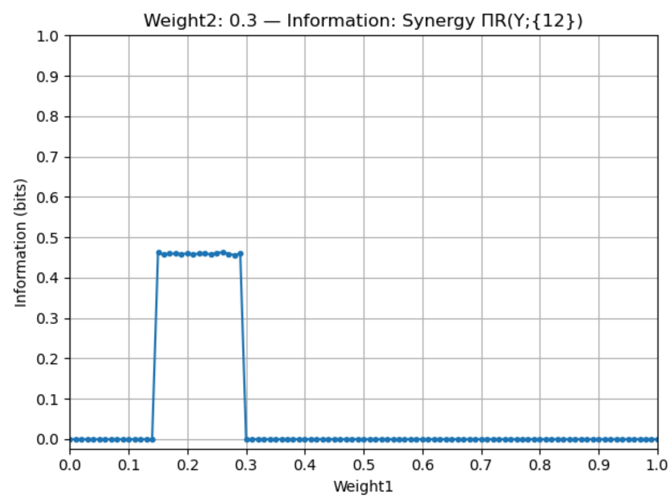
Over the past eight weeks, I have written over a thousand lines of code in Python and made a lot of realizations through this project. One of the first shifts I made was a slight tweak to the entire project. Originally, I was only going to focus on just the synergistic information. However, as I was learning more, I realized there was no reason not to measure all types of information and really get a complete understanding of how changes within the network affect all information overall. Following this, I soon ran into a major computational challenge, ironically, the very issue I am trying to help fix. Calculating information for three or four sources took less than one second, and five sources required slightly more than one second. However, adding a sixth source increased computation time dramatically, going from one second to over an hour and I estimate that a calculation involving seven sources could take decades to finish. Although I anticipated computational intensity with increased sources, the threshold for computational infeasibility was much lower than I thought it would be. Another challenge arose just from interpreting the results of larger networks, which generated thousands of data points (a fraction of which is shown in the picture to the right). However, it turned out that these were hardly major roadblocks. All it meant was that there had to be more of a focus on measuring the smaller differences in systems of just a few sources. This turned into making it so every single possible configuration would be calculated on to ensure the most “complete” picture. The very large set of data had a rather simple solution as well, of just finding ways to separate all the data into different categories and graph all the data points. In the end, this approach actually simplifies data analysis, as results could



be effectively visualized through graphs, allowing clearer interpretation and giving more data to analyze.

By the end of this FURSCA project, I successfully developed a highly manipulable artificial neural network capable of easily adjusting the number of sources and automatically evaluating hundreds of different connection strengths in every possible configuration. All three types of information were computed and visualized graphically (Some examples shown to the right). With most of the coding completed, the final step is a straightforward task of analyzing numerous graphs. This analysis, which I plan to undertake in my spare time during the fall semester, will aim to clearly define the factors influencing information. Specifically, it will hopefully clarify under what conditions certain nodes can be ignored or how larger networks can effectively be decomposed into smaller, manageable subsets for more detailed study.





Through this project, I gained valuable coding skills in Python, which have become increasingly essential in my field of physics. Specifically, I learned how to simulate complex real-world systems, a widely used technique in physics research, laying the foundation for future simulations I will do in my career. Additionally, I gained deep insights into information theory, a rapidly growing area with broad applications ranging from optimizing cellular communications to advancing quantum computing. This knowledge will also greatly benefit my future academic and professional career.

I look forward to completing my data analysis this fall and presenting the final results at the Elkin Isaac Symposium in the spring. Finally, I extend my heartfelt thanks to my advisor, Dr. Cho, for guiding me through complex concepts and patiently addressing my many (sometimes stupid) questions. I also want to sincerely thank the Provost's Office and all of Albion College’s donors for their generous support, enabling students like me to truly investigate their passions and gain invaluable research experience along the way.