Hello everyone, Welcome to my project station! My name is Ellen Wang from Horace Mann School in Bronx NY.

This project I have been working on since the beginning of 2023 is an interdisciplinary investigation that innovates a **classical statistical physics** model to address the pressing issue of Arctic sea ice loss with the assistance of modern deep learning algorithm.

To begin, two striking estimates by NASA here may quickly give you an idea about the critical importance of study sea ice decline

* First, the September Arctic sea ice, which is normally the minimum ice coverage during a year, is estimated to be shrinking at an astonishing rate of 12.3% per decade;
* Second, the oldest and thickest ice in the Arctic has been declining by a stunning 95% over the past 30 years.

These numbers may be barely remotely relatable, but this is what they imply: if the Arctic sea ice continues shrinking at the current rate as these numbers indicated, some researchers actually predict that the “Blue Ocean Event,” which is an “ice-free” Arctic Ocean, may take place in the 2030s.

Imagine those polar bears who rely on sea ice for resting, hunting, and breeding! Here is a breathtaking picture, called “Ice Bed,” which in early Feb won [Wildlife Photographer of the Year People’s Choice Award](https://www.cnn.com/2023/11/28/travel/wildlife-photographer-of-year-peoples-choice-scli-intl/index.html), and had stirred up strong emotions among millions of viewers like you and me. It may happen very soon that those polar bears as the one in the picture may not be able to even find an icebed to rest **AT ALL!**

Even worse, the humankind just witnessed the **most sizzling** July last year, and the year 2023 was recorded as the hottest year on the earth. It is evidently to better understand the Arctic sea ice evolution, to better prepare for the **enormous** environmental and economic consequences and come up with **timely and effective** solutions.

**However, a**mong the large literature that research the alarming sea ice loss, some of them have engaged modern technologies such as machine learning. However, what has been missing is the identification of fundamental physical principles underlying the sea ice dynamics. AND THIS IS EXACTLY WHAT MY RESEARCH, WHICH ENGAGES THE ISING MODEL IN STATISTICAL PHYSIS IS AIMING TO CONTRIBUTE.

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Luckily, the data for my study called NRTSI, has been made publicly accessible by the National Snow and Ice Data Center. Here is a quick look of the NRTSI data on 09/16/2022; and my study focuses on a specific geographic region bounded by the black square, ranging from the East Siberian Sea (to the top of the box) and the Beaufort Sea (to the left of the box) to near the polar point, about 2.25 million square kilometers.

The backbone of my study to identify the physical mechanism underlying sea ice dynamics is ISING MODEL, initially proposed in Ernst Ising’s 1924 Ph.D. thesis, to explain ferromagnetism and phase transitions, but seeing wide success beyond statistical physics, such as in biology, environmental science, economics and financial analyses etc. More excitingly, The reversible phase transition between ice and water makes the Ising model a **great tool** to study the dynamics of a surface region with the co-existence of both states, like the Arctic! 2024 is celebrating the 100-year birthday of this versatile model, I am fortunate enough to employ it to join the pioneering scientific research that address global warming!

Here is the framework of a classical IM, where the Hamiltonian, or the energy function of a Ising lattice is determined by the interaction of adjacent spins and the impact of external forces on the spins.

Very importantly, I innovate this 2-dimentional binary IM with two new features that better captures the reality of sea ice dynamics:

* First, I allow the spin values to be continuous in between, with +1 and -1, indicating a fractional ice coverage converted from the original data.
* Second, I introduce an innovative inertia factor I that represent the natural resistance to any state change. The revised probability of flipping therefore relies on −𝐼|𝜎′𝑖−𝜎𝑖|, which accounts for the energy needed to overcome the inertia of the spin change. Intuitively speaking, this term can be thought of as the latent heat needed for the ice/water phase transition in classical thermodynamics. According to my experiment, this factor proved to be very critical for the performance of the model.

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Computationally, finding the best-fit Ising interaction parameters that fit the data the closest, or the so-called “inverse ising problem,” is quite complex. For this purpose, I harnessed the power of modern cutting-edge deep learning technology, by which the Ising lattice initial and final states of a simulation period, which is consistently half a month apart, are fed to train a Convolutional neural network, which **widely** known to be probably the best image recognition artificial intelligence algorithm.

Here are some more details on the simulation procedures and the CNN architecture employed in my study:

* For each initial state of the half-month simulation period from 06/01 to 01/01, we randomly select 10,000 sets of parameters (*J, B0, Bx, By,* *I*). Given each set of parameters, I follow the Markov Chain Monte Carlo simulation with 50,000 iterations that employs the metropolis-hastings method to generate a final state Ising lattice.
* These simulated images for all simulation periods altogether (totalling more than 100,00 pairs) are used to train a CNN, which consists of four convolutional layers with a kernel shape (3, 3), with increasing filter counts from 16 to 32, 64, and 128 in the last convolutional layer. Zero padding and strides (1, 1) are used to ensure coverage of the entire input grid. Every convolutional layer is followed by a max pooling layer of pool size (2, 2) that summarizes the crucial features and reduces the layer size. The outputs of the last max pooling layer are flattened and followed by a fully connected dense layer with LeakyReLU activation. A dropout layer with dropout ratio 20% is applied to avoid overfitting. The outputs are fed to the final dense layer with 5 neurons, which is the number of IM parameters to be solved.

The total number of trainable CNN parameters stays at 213,101, making the training process a relatively small but tractable deep learning algorithm. Once well trained and all CNN parameters are saved, the CNN will predict the 5 Ising parameters for any two actual initial and final stage configurations fed into the CNN.

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By combining the novel Ising Model with CNN, my study has delivered excellent results. Here I am first showing you the result for 2023, which is recorded as the hottest year on the earth:

By reviewing the CNN-predicted parameters, a few observations are worth discussion:

* The spin interaction coefficient J and the inertia factor are relatively stable across periods but the external force parameters 𝐵0, 𝐵𝑥 , and 𝐵𝑦 display large variations across different time periods.
* More closely, 𝐵0 is positive from June 1st to Sept 16th and turns negative afterwards. This may be explained intuitively by the seasonal ambient temperature; however, as the ambient temperature cools down from Aug to Sept, some other environmental factors that may impact 𝐵0 must be playing a role in the picture, including albedo or jet streams. these factors can be further investigated in future research.

Visually, I am also showing a comparison between the actual and the simulated images of the 2023 sea ice evolution based on the CNN predicted parameters. As you can see, the simulated images display **striking similarity** with the actual ice/water configurations. This is actually the case **across all** the years observed in my dataset.

The numerical difference (the absolute value of simulated minus actual for each cell) between the simulated and actual images are illustrated by the heatmaps for better visualization. In the heatmap, light yellow color means no difference, red shows large difference. As seen, the red patches, indicating discrepancy between simulation and actual, are consistently small and mostly take place at the borders between ice and water. This is not surprising: the IM needs improvement to perfectly model these boundary granularities, but it does have strong explanatory power to capture the overall patterns.

Moreover, I calculated two numerical measures from the simulation results based on the predicted Ising parameters, and compare them with the data statistics, the ice coverage percentage, which is the arithmetic mean of ice coverage across the entire lattice, and the ice extent, which is the percentage of areas with at least 15% ice coverage. As can be seen in this figure, both measures calculated from the simulation match **closely** with the data statistics, which validates the very strong explanatory power of my model.

Such striking similarity is also observed if we check on some other years I have experimented with, including 2022 and 2012 when the lowest ice extent was recorded. More interestingly, if we apply the CNN predicted Ising parameters to simulate the sea ice evolution at a smaller interval, say on a daily basis, such striking similarity again SUSTAINS! Here I am showing you how close the simulated daily evolution is to the actual images, for a melting and a freezing cycle in 2022. It is absolutely confirmed the model’s capability to preserve more granular ice/water dynamics.

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So to conclude, my study revealed the extraordinary power of the continuous spin Ising model with the novel inertia factor to replicate and explain sea ice dynamics, when trained with a CNN. The study not only identified the substantial impact of the external forces, which can be one direction to enhance the modeling of Arctic sea ice dynamics, but also validates the vast potential of coupling classical physics with modern deep learning technology in environmental studies and other disciplines. Moving forward, I am hoping to bring my study to the next level by engaging larger and deeper neural networks and exploring the quantum Ising model and quantum neural network, which I am currently studying.

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Thanks lot for the opportunity to share my project and I would like to answer any questions you may have.