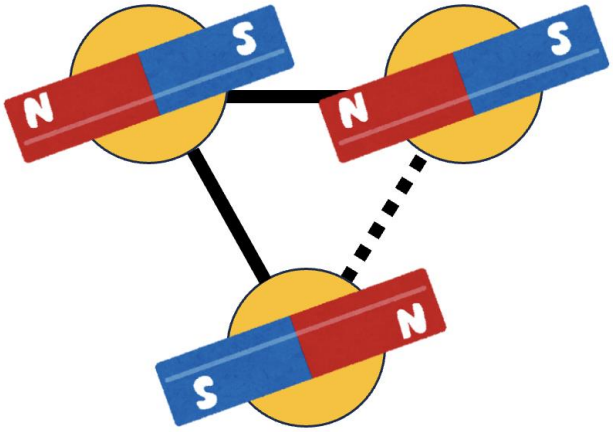
The Structure of Glass: from physics to AI

Have you ever wondered what state glass is in? Is it a solid, a liquid, or a gas? While most people have not thought of the question or would assume without a doubt that it's a solid, glass is actually better described as a hard liquid. Such a unique property of glass had puzzled scientists and was eventually explained by the theory of "spin glass". Time passed from the study of glass, and Giorgio Parisi, a theoretical physicist in Italy, won the Nobel Prize in 2021 for a series of studies on complex systems that began with the research on spin glass. One of the main reasons for his recognition is the fact that the ideas and technics invented during spin glass research have expanded beyond physics and are now utilized in neuroscience, computer science, and even artificial intelligence as well. This essay aims to introduce such a fascinating and interdisciplinary field of spin glass and its amazing application, especially in AI.

The concept of spin glass was initially developed through the examination of magnets. These metallic materials that can be magnetized are composed of minute entities referred to as spins, which function like miniature magnets. Each of these spins possesses an orientation like a real magnet, and they align so that adjacent spins face the same direction. This alignment leads to the synchronization of all the spins, and eventually, the set of them acts as a giant magnet.

Now let us explore what would happen if we added magnetic metal to another metal with a different property of trying to orient itself in the opposite direction of its neighboring spins. This process alters the behavior of the spins, causing some to prefer facing in the opposite direction. Still, others prefer facing the same direction, making it

impossible to meet the demands of all spins. As a result, parts of spins must be patient and turn in the direction they don't want to face. This creates a complex system called the glass state, a hard substance that is not crystalline, and spins are arranged disorderly. It is a brief overview of what the glass is.



Many researchers have been drawn to the study of spin glass, both experimentally and theoretically. What makes it so intriguing are its "model simplicity" and "sudden change" characteristics.

Firstly, the glass structure is highly intricate, making it challenging to determine its true nature. However, the first mathematical model of spin glass proposed was very simple, but nevertheless, it could explain its complex nature well.

Secondly, in the glass state, altering the temperature results in a discontinuous shift in various physical quantities, referred to as a phase transition in physics. To explain what the phase transition is, another intuitive example is the change from ice to water. You may have seen a mixture of water and ice, but no one has ever seen anything between water and ice. This is also a sudden change of state. It is an unusual feature, as many other

functions that come up in other areas of physics or around the world are expected to be smooth enough.

Spin glass theory started from a simple problem setting but produced diverse phases and nontrivial results, such as the phase transition. They are why spin glass theory is scientifically significant.

It is incredible how complex phenomena with correlations like glass exist everywhere in our life. Even the structure of the community in human society, brain, and graph theory also has complex glass-like structure and is of interest to physicists. Moreover, AI techniques, such as the now famous sentence-generating robot called chat-GPT, have been suggested to contain spin glass-like structures. As evidence, it was empirically found that increasing the number of parameters to a few tens of millions caused a “sudden” improvement in the performance of GPT3. This phenomenon is, for the physicist, the very phase transition itself.

But why does machine learning have something in common with physics? This is because deep learning, a well-known method of machine learning, has the same structure as a molecule in that the deep neural network is composed of many “spins,” and each spin interacts with the other. Therefore, hopefully, we can use the same method used in the analysis of spin glass in order to investigate the nature of machine learning. In fact, it has been calculated from spin glass theory in simpler machine learning models that a phase transition occurs in the middle of learning, and the performance suddenly changes.

The results we obtained are not in line with our intuition: rather than gradual changes, we observed sudden ones. The traditional physical approach to AI research will likely contribute to elucidating the principles of learning by revealing such an exciting structure

through which AI learns.

In conclusion, the study of spin glass properties started in physics and has led to the development of a new framework for dealing with the world's complexity. To date, however, there are still many unsolved problems. For example, today's successful artificial intelligence uses large-scale models, but is the largeness really necessary? This research field may provide clues to solving numerous problems in the future.

References

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Assistive Technologies

I used Grammarly to correct my misspelling and rephrase in a better way.