# Statistical Physics in Complex Systems: Challenges and Future Prospects

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The 19th century saw significant advancements in thermodynamics and the kinetic theory of gases, with J. C. Maxwell and L. E. Boltzmann playing key roles in the development of statistical physics through their work on the distribution of single-particle states.[1] At the beginning of the 20th century, J. W. Gibbs established modern equilibrium statistical physics based on the statistical distribution of system microstates and the concept of ensembles. Subsequently, statistical physics expanded into the quantum and nonequilibrium domains. Since the first experimental observation of critical phenomena in 1869, the theory of phase transitions and critical phenomena has evolved considerably. Early work, such as van der Waals theory for gas-liquid systems, was followed by Landau's mean-field theory. A landmark achievement in this field was Onsager's exact solution for the two-dimensional Ising model. Later, Wilson's renormalization group theory[2] established this area as a cornerstone of statistical physics research. Over the past few decades, the scope of statistical physics has broadened beyond traditional simple models to encompass diverse complex systems. These systems are composed of numerous interacting individuals that exhibit collective behaviors, such as correlation, cooperation, and emergence, that are not simply the sum of individual properties. As P. W. Anderson stated in his 1972 science article titled "More is Different", the behavior of large complex aggregates of elementary particles cannot be understood through simple extrapolation from the properties of a few particles.[3] This shift in focus is reflected in several Nobel Prizes in Physics. In 1991, Pierre-Gilles de Gennes received the award for generalizing methods used to study order phenomena in simple systems to more complex forms of matter, notably liquid crystals and polymers. In 2021, the prize was awarded to Syukuro Manabe, Klaus Hasselmann, and Giorgio Parisi for their groundbreaking work in climate modeling and understanding complex systems. Finally, in 2024, John Hopfield and Geoffrey Hinton were honored for their foundational work on artificial neural networks, a field with deep roots in statistical physics that has revolutionized machine learning.

The study of complex systems now spans diverse fields, including the physical sciences,[4,5] material sciences,[6] life sciences,[7] and Earth sciences,[8] among others.[9–11] Within these disciplines, important phenomena are not determined solely by individual behavior but rather involve emergence and critical phenomena arising from the complex interactions among system components. In the physical sciences, the emergence and critical phenomena in complex systems are related to a variety of subjects, including many-body quantum systems,[12] soft matter,[13,14] active matter,[15,16] disordered and glassy systems,[17] chaotic systems,[18] and complex fluids and turbulence.[19] These phenomena are also closely associated with phase transitions,[20] self-organization,[21,22] and nonlinear dynamics.[23] In material sciences, order can emerge in soft matter systems such as polymers, liquid crystals, and colloids. Life sciences explore self-organization in biological systems at various levels, including brain systems.[24] In the Earth and social sciences, global warming has led to the emergence of critical elements with global impacts, involving atmospheric and climate systems, ecosystems, ocean systems, and social systems. Studying these complex systems from a statistical physics perspective has become increasingly urgent. Concurrently, exploring statistical physics patterns, particularly their emergence and critical phenomena, using artificial intelligence and machine learning[25] is crucial for the field's continued evolution and advancement.

Traditional statistical physics is well suited for equilibrium systems; however, real-world systems often operate out of equilibrium, displaying nonlinearity, complexity, emergence, and multiscale features. Therefore, there

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is an urgent need to develop new nonequilibrium statistical physics paradigms based on in-depth studies of such systems. Experiments, simulations, and theories are essential tools for studying complex systems. Experiments allow direct observation of system behavior, verification of theoretical models, and discovery of new phenomena and laws. With the rapid development of computer and artificial intelligence technologies, numerical simulations have become important tools. By constructing system models, they can simulate the evolution of complex systems and predict their phase transitions and emergent behaviors. Developing a theoretical framework, which is currently lacking, especially for far-from-equilibrium systems, is at the core of complex system studies. By establishing such models and frameworks, we can abstract and generalize system behavior, revealing the essence and laws of emergence and critical phenomena. The integration of experiments, simulations, and theory is essential for developing new paradigms in nonequilibrium statistical physics, which are crucial for advancing our understanding of the dynamic and complex behavior of real-world systems.

We also note that many macroscopic and complex systems lack reliable simulation and experimental data, with only observational data available. This underscores the significance of big data research.[26–30] We anticipate that future research in the statistical physics of complex systems will increasingly be driven by big data. This research will build upon and develop traditional statistical physics ideas and methods, incorporating artificial intelligence technology to develop new general theories. This approach will deepen our understanding of complex system behaviors and enhance our ability to predict and control collective behaviors, phase transitions, and critical phenomena across diverse complex systems.

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