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Statistical Physics Learning Difficulties and Instructional Strategies: A Systematic Literature Review Supporting Quality Science Education (SDG 4)

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Abstract: This systematic literature review (SLR) examines the topics in statistical physics that students find difficult, the factors underlying these difficulties, and the instructional strategies used to address them. Following PRISMA guidelines, 153 records were identified from Scopus through Publish or Perish, reduced through identification, screening, and eligibility stages to 17 included articles published between 2000 and 2024. The most challenging topics are microscopic/macroscopic states, entropy, the Boltzmann factor and distribution, partition functions, and the Fermi-Dirac distribution. Difficulties stem mainly from limited mathematical and representational skills, scarce visualization media, and the high abstraction of the concepts. Reported strategies, including computer simulation, laboratory experiments, inquiry-based learning, Clicker Question Sequences, educational games, and Excel- or Desmos-based simulation, show promising but unevenly evaluated effectiveness: most are theoretical proposals, while only a minority report empirical classroom testing. The novelty of this review lies in showing that, despite twenty-four years of proposed solutions, comprehensive effectiveness evaluation and supporting instructional materials remain scarce. These findings give instructors and curriculum designers an empirical basis for prioritizing which statistical physics topics and strategies most need rigorous, classroom-tested development.

Keywords: Bose-Einstein; Computer simulation; Fermi-Dirac; Maxwell-Boltzmann; Statistical physics

Introduction

Advanced physics covers essential topics such as thermodynamics, statistical mechanics, electromagnetism, quantum physics, core physics, solid-state physics, and particle physics, the latter being highly relevant for understanding microstates and probability distributions in statistical mechanics. Advanced physics learning often requires a complex and abstract understanding of mathematics. Mathematics functions not merely as a computational tool but also as a primary language and epistemological instrument in physics, essential for modeling, analyzing, and interpreting physical phenomena (Galili, 2018). However, in the practice of physics education, conceptual understanding is often underemphasized in favor of mastering mathematical principles. As a result, many students can carry out calculations without truly grasping the physical meanings of the mathematical symbols they use.

This issue is particularly evident in statistical physics, which involves abstract concepts such as entropy, partition functions, and probability densities. These topics demand not only mathematical fluency but also conceptual clarity. Due to their high level of abstraction, the mathematical models used in physics frequently pose significant challenges for students and may hinder the development of deep scientific

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understanding (Palmgren & Rasa, 2024). Therefore, students' ability to bridge mathematical formalism with physical interpretation becomes a critical factor for successful learning in advanced physics, including statistical physics (Karam & Krey, 2015).

One essential prerequisite for understanding statistical physics is mastering thermodynamic materials. However, research shows that students often experience difficulties and misconceptions in this topic, particularly regarding entropy, the function of state, and free energy (Atarés et al., 2021; Bezen, 2016; Sozbilir, 2003; Styer & Styer, 2019; Wu & Wu, 2020). These misconceptions and difficulties can directly impact students' understanding of statistical physics, a vital field of study for the development of technology and environmental solutions. Although the role of statistical physics is vital, students often find learning this topic challenging due to its abstract nature and complex mathematical equations. These difficulties are not only encountered by undergraduate students, but also by advanced students in master's and doctoral programs, who are required to apply statistical physics principles in research, data analysis, and modeling of complex physical systems.

Statistical physics has a wide range of applications that underlie many modern technologies, such as artificial intelligence (machine learning) and deep learning algorithms (Bahri et al., 2020). For example, statistical physics is used to model traffic distribution and support the design of adaptive traffic control algorithms (Furtlehner, 2020; Jerath et al., 2015). In the field of environment, statistical physics concepts are applied to optimize adsorbents in reducing pollutants in wastewater and model the adsorption process of dyes in biomass (Farhan et al., 2018; Lamine, 2017; Pang et al., 2019; Sozbilir, 2003). In various countries with advanced scientific and technological development, such as Israel, the United States, Russia, and China, statistical physics is not only a foundational subject in physics education but also serves as a critical tool in technological innovation, ranging from quantum computing, nanotechnology, to climate modeling. These countries have invested significantly in research and education to advance statistical physics as a core competence in science and engineering. Thus, mastery of statistical physics concepts is academically essential and has significant practical relevance. Therefore, conducting a systematic literature review (SLR) to identify difficult topics, the factors that cause difficulties, and solutions that have been implemented to overcome these challenges is essential for improving the teaching and learning process of statistical physics at all levels of education.

Several SLRs in physics education have been conducted, such as a study on the use of eye tracking in physics education, which shows a great focus on the topic of mechanics (Hahn, 2022) and the importance of virtual technology in optical, thermodynamic, and acoustic learning (Wang et al., 2024). In addition, physics education innovations generally still focus on didactic aspects, not on students' conceptual development (Campos et al., 2020). However, specialized studies on innovations in statistical physics learning remain limited. Therefore, this study focuses on systematic literature reviews (SLRs) to fill these gaps, aiming to identify the main challenges and solutions in statistical physics learning.

This research aims to systematically identify the most challenging topics in statistical physics for students, analyze the contributing factors to these difficulties, and evaluate the solutions that have been proposed and implemented to address these challenges. Specifically, this study seeks to provide empirical insights that support the development of effective learning strategies, inform curriculum design, and enrich the literature on physics education with innovative and evidence-based approaches. To achieve these aims, this Systematic Literature Review (SLR) addresses the following research questions: what topics in statistical physics are difficult for students to understand and what factors contribute to these difficulties, and what solutions have been implemented to overcome these difficulties and how do they contribute to improving understanding.

Method

This study uses the Systematic Literature Review (SLR) method to identify, assess, interpret, and analyze research findings relevant to the research topic or question. This study aims to conduct SLR related to students' difficulties in studying statistical physics, its causes, and solutions used to overcome these difficulties. The SLR method used is PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), which includes four steps: identification, screening, eligibility, and inclusion criteria. In the final step, inclusion criteria are applied to analyze the remaining articles (Azril et al., 2020), as summarized in Figure 1.

In the identification stage, articles were retrieved from the Scopus database using the Publish or Perish (PoP) application, restricted to the publication range 2000–2024. Three keyword strings were used: "solutions in teaching statistical physics", "statistical physics education difficulties", and "statistical mechanics" AND "teaching", yielding 22, 31, and 100 records respectively, for a total of 153 records (Table 1). Before screening, 3 duplicate records and 94 records judged ineligible by

automated and manual relevance checks (e.g., wrong document type, non-physics-education focus) were removed, leaving 56 records for title and abstract screening.

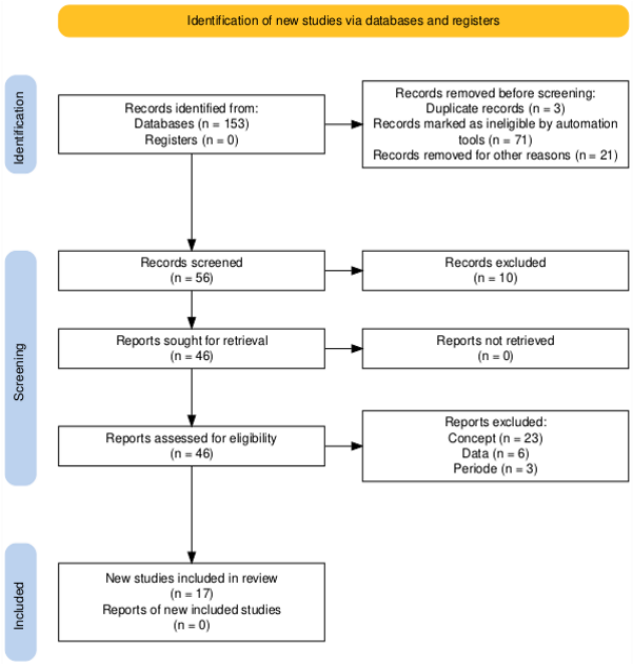


Figure 1. Flowchart PRISMA

Table 1. Number of articles by keyword on PoP

Key word	Number of articles
"Solutions in teaching statistical physics"	22
"Statistical physics education difficulties"	31
"Statistical mechanics" AND "teaching"	100

In the screening stage, the 56 records were evaluated against the inclusion and exclusion criteria summarized in Table 2: article type (journal research articles and proceedings included; books, book chapters, review articles, dissertations, and theses excluded), language (English included; non-English excluded), and publication period (2000–2024 included; pre-2000 excluded). This step excluded 10 records, leaving 46 reports sought for retrieval; all 46 full texts were successfully retrieved.

Table 2. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Article type	Journal (research articles), Proceeding	Books, Chapters in books, review articles, dissertation or thesis
Language	English	Non-English
Period	2000 - 2024	Publish before 2000

In the eligibility stage, the 46 retrieved reports were assessed in full text against the research context and objectives, through three steps: abstract screening, detailed analysis against the established selection criteria with results tabulated, and synthesis of all findings into a single document. Of the 46 reports assessed, 29 were excluded for being conceptually unrelated to the review's focus, for insufficient or incomplete data, or for falling outside the intended scope despite meeting the basic period and language criteria. This eligibility step yielded the final 17 articles included in the qualitative synthesis (46 − 29 = 17), consistent with the totals reported in Tables 3 and 4, where six articles address learning difficulties (Table 3), fourteen articles address instructional solutions (Table 4), and three articles (Justice et al., 2020a; Sharma & Ahluwalia, 2015; Smith et al., 2015) report both a difficulty and a corresponding solution and therefore appear in both tables, giving 6 + 14 − 3 = 17 unique included studies.

Results and Discussion

An analysis of the selected articles was conducted to identify the difficulties associated with learning statistical physics, the factors contributing to these difficulties, and the strategies employed to address them. The results are presented in Tables 3 and 4.

Table 3. Analysis of difficult material and causes of difficulty

Author, year	Title	Research Method	Key findings	Difficult topics	Factors that cause difficulties
Koerfer & Gregorcic (2024)	Exploring student reasoning in statistical mechanics: Identifying challenges in problem-solving groups	Qualitative	Students find it challenging to solve statistical mechanics problems.	Microscopic, macroscopic states, differentiated and indistinguishable particles, entropy, Boltzmann distribution and, partition function.	Limitations of mathematical understanding
Justice et al. (2020b)	Student understanding of Fermi energy, the Fermi-Dirac distribution and total	Mixed method	Students have difficulty understanding the state density with free electrons and interpreting the Fermi energy	Fermi Dirac distribution fermi energy, and total energy of electron gas, fermi energy	Lack of visualization media

Author, year	Title	Research Method	Key findings	Difficult topics	Factors that cause difficulties
	electronic energy of a free electron gas		distribution function graph	distribution graph vs temperature	
Smith et al. (2013)	Identifying student difficulties with conflicting ideas in statistical mechanics	Qualitative	Students have difficulty understanding the graph showing the relationship between the Boltzmann factor and the partition function	Boltzmann factor	Lack of visualization media
Smith et al. (2010)	Addressing Student Difficulties with Statistical Mechanics: The Boltzmann Factor	Qualitative	Students have difficulty understanding the relationship between the Boltzmann factor, partition functions, and probability	Relationship of Boltzmann Factor to partition function	Limitations of mathematical ability
Sharma & Ahluwalia (2015)	Diagnosing alternative conceptions of Fermi energy among undergraduate students	Qualitative	Students have difficulty connecting fermic energy, fermic energy distribution with various representations.	Fermy energy, distribution Fermy energy	Lack of representation ability
Lee (2001)	How to teach statistical thermal physics in an introductory physics course	Qualitative	Students have difficulty understanding the relationship between entropy, temperature, and the Boltzmann factor	Entropy, temperature and Boltzmann factor	lack of mathematical skills and abstract materials

Table 4 presents an analysis of solutions applied to overcome students' difficulties in learning statistical physics. This analysis includes articles summarized based on the components of the author's name, year, title, research method, main findings, statistical physics topics, and methods or strategies used.

Table 4. Strategies and methods used in learning statistical physics

Author, year	Title	Research method	Material topics	Key findings	Strategies/Methods Applied
Beltran (2023)	Quantum Bose–Einstein Statistics for Indistinguishable Concepts in Human Language	Theoretical analysis	Bose Einstein statistical distribution	The combination of the concepts of "number" and "substantive concept," such as "eleven animals" that are identical and indistinguishable, results in a statistical structure similar to the Bose-Einstein distribution	Data analysis using the Kullback–Leibler divergence method
Filho & Ferreira (2021)	Indistinguishability and Counting: Teaching the role of different interpretations in Quantum Mechanics	Theoretical analysis	Distributed by Maxwell Boltzmann, Bose Einstein, Fermi Dirac	Applying the correspondence principle to interpret the concept of particles is indistinguishable from classical and quantum statistical mechanics	Correspondence principle for counting differentiated and indistinguishable particles in statistical and quantum mechanics
Jameson & Brüschweiler (2020)	Active Learning Approach for an Intuitive Understanding of the Boltzmann Distribution by Basic Computer Simulations	Theoretical analysis	Maxwell Boltzmann Distribution	Application of learning and computer simulation approaches to understand Maxwell Boltzmann's distribution	Active learning and computer simulations
Bhattacharyya & Dawlaty (2019)	Teaching Entropi from phase space perspective: connecting the statistical and thermodynamic views	Theoretical analysis	Entropy	The relationship of entropy from thermodynamics (Clausius equation) with entropy in statistics	Mathematical simplification

Author, year	Title	Research method	Material topics	Key findings	Strategies/Methods Applied
	using a simple one-dimensional model			(Boltzmann equation) can be explained by mathematical analysis in a 1-dimensional phase space	
Saw (2017)	Cognitive load theory and the use of worked example as an instructional strategi in physics for distance learner: A preliminary study.	Quantitative	Fermy Dirac distribution	Instructional strategies using examples effectively increase students' understanding of concepts and reduce students' cognitive burden.	Instructive strategy using examples
Engelhardt et al. (2015)	Simple and synergistic ways to understand the Boltzmann distribution function	Theoretical analysis	Boltzmann distribution functions	Simple computational simulation experiments and a combination of laboratory experiments and simulations can help one understand Boltzmann's distribution function.	Computational simulation experiments or a combination of laboratory experiments and computer simulation
Fernández (2015)	A simple way of approximating the canonical partition functions in statistical mechanics.	Theoretical analysis	Partition function	Deterioration of partition function using the Mac-Laurin series	Mathematical simplification
Müller (2014)	The Boltzmann factor: a simplified derivation	Theoretical analysis	Boltzmann factor	The Boltzmann factor can be derived from a microcanonical approach without a Lagrange multiplier	Mathematical simplification
Battaglia et al. (2015)	An inquiry-based approach to Maxwell distribution: a case study with engineering students	Mix method	Maxwell-Boltzmann Distribution	An experiment-based inquiry approach increases students' understanding of concepts	Inquiry approach
Sharma & Ahluwalia (2015)	Diagnosing Alternative Conceptions of Fermi Energy among Undergraduate Students.	Mix method	Energy Fermi	The application of Excel spreads can help reduce students' misconceptions about Fermy energy	Excel spread sheet simulation
Justice et al. (2020b)	Student understanding of Fermi energy, the Fermi-Dirac distribution and total electronic energy of a free electron gas	Mix method	Energy Fermi	Students' understanding of Fermy energy material and electrified gas energy distribution increased after learning through the use of CQS.	Clicker Question Sequence Fermy energy
Smith et al. (2010)	Addressing Student Difficulties with Statistical Mechanics: The Boltzmann Factor	Qualitative	Boltzmann factor	The application of guided inquiry-based worksheets improves students' understanding of concepts	Guided inquiry
Ellis et al. (2018)	An Experimental Approach to Teaching and Learning Elementary Statistical Mechanics	Theoretical analysis	Entropy	The use of box equilibrium distribution of beads can demonstrate entropy	Laboratory experiments
Hanson & Michalek (2006)	Give them money: the Boltzmann game a classroom or laboratory activity modeling entropy change and the distribution of energy in chemical system	Qualitative	Microscopic, macroscopic states and entropy	The application of Boltzmann-games makes it easier for students to understand microscopic, macroscopic states, and entropy	Game

The Topic of Statistical Physics is Difficult for Students to Understand, and the Factors that Cause It

The findings of the analysis results show that the materials in statistical physics that are still considered difficult by students are microscopic states, macroscopic states, differentiated and indistinguishable particles, entropy, Boltzmann factor, Boltzmann distribution and partition functions, Fermi energy, and Fermi energy distribution. The factors causing students' difficulties were identified, namely the limited understanding of mathematics and representation (Koerfer, 2024; Lee, 2001; Sharma & Ahluwalia, 2015), lack of abstract concept visualization media (Justice et al., 2020b), high abstraction of the theoretical concepts of static physics (Lee, 2001).

Limited understanding of mathematics and representation skills causes students to experience difficulties in understanding statistical physics. The role of mathematics is very significant in mastering the concepts of physics. The lack of visual representation of physics concepts in the form of text, images, diagrams, and graphs makes it difficult for students to understand the concepts (Redish, 2023; Shubha & Meera, 2019). Visual representation is adequate for understanding the physics concepts of students with low initial knowledge (Bahtaji, 2020). The use of text and visual representations provides more benefits, not only improving concept understanding but also reducing the cognitive load of students and improving critical thinking skills (Abdurrahman, 2019; Ainsworth, 2008; Herrlinger et al., 2016). The transition between physics and mathematics is essential because teaching mathematics in mathematics learning differs from teaching mathematics to physics learning (Redish & Kuo, 2015). Thus, learning statistical physics using a variety of representations, including mathematical representations, visualizations, and texts, has the potential to improve understanding of concepts.

Strategies to Overcome Students' Difficulties in Understanding Statistical Physics

Based on the results of the previous research review in Table 4, the learning strategies have been effective in overcoming students' difficulties in understanding statistical physics, namely:

Combination of Laboratory Experiments and Computer Simulations

To address students' difficulties in comprehending abstract concepts in statistical physics, laboratory experiments and computer simulations have been widely implemented. Laboratory-based activities play a crucial role in facilitating students' understanding of entropy by enabling direct observation of physical phenomena (Ellis, 2018). This approach bridges theoretical concepts with empirical data, thereby enhancing conceptual clarity and fostering deeper learning (Wieman & Holmes, 2015). Meanwhile, computer simulations provide dynamic visualizations of abstract principles, such as the Boltzmann distribution, allowing students to grasp complex ideas more effectively (Engelhardt et al., 2015; Jameson & Brüschweiler, 2020). The integration of laboratory experiments with computer simulations has proven to be an effective strategy in reinforcing students' understanding of otherwise challenging and abstract physics concepts (Flegr et al., 2023). Therefore, this combined approach significantly contributes to the comprehensive mastery of statistical physics among students.

Strategic Inquiry

The implementation of inquiry-based strategies in statistical physics instruction has been proven effective in enhancing students' conceptual understanding. For instance, guided inquiry approaches have been shown to strengthen students' grasp of key concepts such as distribution functions and the Boltzmann factor (Battaglia, 2016; Smith, 2015). Moreover, the integration of inquiry strategies with Clicker Question Sequences has demonstrated the potential to reduce students' cognitive load when learning complex topics such as the Fermi-Dirac distribution, Fermi energy, and the energy distribution of electron gases (Justice et al., 2020b; Saw, 2017). Inquiry-based learning has also been associated with improvements in students' scientific skills, conceptual mastery, science process skills, and self-efficacy (Husnaini & Chen, 2019; Rodriguez et al., 2020; Shi et al., 2020; Wang et al., 2015). Therefore, inquiry-based strategies should be considered a central component in the design of effective statistical physics instruction.

The application of CQS in advanced physics learning effectively supports the improvement of concept understanding. Practical application of CQS in research-based advanced physics learning provides scaffolding support to form a good physics knowledge structure to improve (Justice et al., 2020a). Implementing CQS will improve conceptual understanding through active interaction, quick feedback, and group discussions (Sayer et al., 2016). Applying CQS-integrated collaborative learning in physics learning can potentially improve students' higher-level thinking skills (Liu et al., 2017).

Application of Excel Spreadsheets, Desmos, and Mathematical Simplification

Statistical physics often involves complex mathematical functions that can be conceptually challenging for students. To address this difficulty,

mathematical expressions are presented through multiple forms of visual representation, such as graphs, illustrations, and data tables, which can be effectively generated using software tools like Microsoft Excel and Desmos (Sharma & Ahluwalia, 2015). These visualizations serve to bridge abstract physical concepts and students' conceptual understanding. Moreover, the complexity of mathematical functions can be reduced by applying simplifications based on students' prior knowledge of fundamental mathematics for instance, the application of the Maclaurin series in deriving the Boltzmann factor (Fernández, 2015; Müller, 2014).

Excel spreadsheet software is familiar to students and can be used to simulate data for various physical parameters (Uddin et al., 2017). Application of Excel simulation in solving mechanical problems (Quale, 2012) and promoting STEM (Benacka, 2016) has received a positive response from high school students. This can be adapted to statistical physics lectures at universities. Integrating visual representations with mathematical simplification strategies has proven to be an effective pedagogical approach in facilitating the learning of statistical physics concepts.

Games

Educational games in statistical physics learning serve as instructional tools designed to facilitate students' understanding of abstract concepts. For instance, the Give the Money game has been employed to help students grasp the concepts of entropy, as well as the distinction between microscopic and macroscopic states (Hanson & Michalek, 2006). The integration of games into physics instruction not only enhances conceptual comprehension but also makes the learning process more engaging and meaningful. Empirical studies indicate that the use of educational games in physics has a positive impact on students' attitudes and interest toward the subject (Baran, 2018), and simultaneously fosters scientific skills (Umrani et al., 2020). Therefore, the systematic planning and development of game-based instructional strategies in statistical physics is essential for improving the overall quality of learning.

The SLR findings imply that the design of statistical physics learning in universities can be done through learning strategies and teaching materials integrating visualization and simulation approaches to overcome difficulties in understanding abstract concepts on the topics of entropy, Boltzmann distribution, Bose-Einstein and Fermi Dirac distribution. Simplifying mathematics and using various textual representations, diagrams, and Excel-based computer simulations or other interactive media can strengthen concept mastery, reduce cognitive load, and encourage active student engagement, ultimately improving critical thinking and problem-solving skills.

Various approaches, methods, and strategies, including active learning approaches, laboratory experiments, and computer simulations, are applied to overcome students' difficulties. These approaches, processes, and techniques have proven effective in increasing students' understanding of abstract concepts, such as Boltzmann distribution and entropy. Applying the inquiry approach and using the Clicker Question Sequence has also positively impacted students' understanding of concepts and active involvement. In addition, using tools such as Excel spreadsheets for simulation makes it easier to understand various physics parameters and helps reduce cognitive load.

Conclusion

Topics that are complex for students to understand include microscopic states, macroscopic, entropy, Boltzmann distribution, and Fermi energy. This difficulty is caused by the limitations of mathematical understanding and representation, the lack of visualization media for abstract concepts, and the high level of abstraction of theoretical concepts. Research shows that a strong knowledge of mathematics and the effective use of visual representations, such as text, images, and diagrams, are essential to help students master the concepts of statistical physics. By simplifying mathematical material and utilizing different types of representations, students can more easily understand complex ideas, which in turn can improve their critical thinking skills. Various approaches, methods, and strategies, including active learning approaches, laboratory experiments, and computer simulations, are applied to overcome students' difficulties. These approaches, methods, and techniques have proven effective in increasing students' understanding of abstract concepts, such as Boltzmann distribution and entropy. Applying the inquiry approach and using the Clicker Question Sequence has also positively impacted students' understanding of concepts and active involvement. In addition, using tools such as Excel spreadsheets for simulation makes it easier to understand various physics parameters and helps reduce cognitive load.

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Conceptualization, investigation, D.E.S.I.A. and P.S.; methodology, formal analysis, resources, data curation, writing – original draft preparation, visualization, funding acquisition, D.E.S.I.A.; software, L.H.; validation, P.S., L.H., and N.W.; writing – review & editing, P.S. and L.H.; supervision, N.W.

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The authors declare no conflict of interest.

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