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Exploring Students' Conceptual Understanding of Statistical Physics Through Multi-Source Learning: A Mixed-Methods Study

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Abstract: Statistical Physics is an intellectually demanding subject that requires students to navigate abstract representations, probabilistic reasoning, and mathematical formalism simultaneously. In today's learning environment, students naturally rely on multiple learning sources, textbooks, YouTube videos, Google searches, and increasingly, explanations generated by artificial intelligence (AI). This mixed-methods study explores how such multi-source engagement shapes conceptual understanding among 28 undergraduate physics education students enrolled in a Statistical Physics course. Quantitative data were collected through a Conceptual Understanding Test (CUT), a multi-source learning questionnaire, a misconception inventory, and rubric-based artifact analysis. Qualitative data were gathered from interviews and reflective journals. The findings reveal that students' conceptual understanding falls within a moderate-to-good range (mean CUT score 69.6), although misconceptions persist, particularly regarding entropy, ensembles, and the partition function. Students with strong conceptual understanding tended to integrate multiple learning sources reflectively constructing coherence across representations while weaker students demonstrated fragmented and shallow engagement. The study concludes that multi-source learning has the potential to reinforce conceptual understanding, provided students develop strategies for synthesizing diverse explanations rather than consuming them indiscriminately.

Keywords: Statistical Physics, Conceptual Understanding, Multi-Source Learning, Mixed Methods.

INTRODUCTION

Teaching Statistical Physics often unfolds as a narrative that moves fluidly between abstract reasoning and concrete phenomena. At times, instruction must linger on concepts that are mathematically precise yet remain inaccessible to direct observation. The interplay between macrostates and microstates is one such example: these constructs are deeply embedded in physical theory but elude sensory experience. Consequently, students must cultivate a flexible mode of thinking, one that enables them to navigate between the calculable and the conceptual. The imaginative shift from enumerable microstates to their macroscopic implications is, in many ways, a cognitive exercise that supports the development of the foundational reasoning required in statistical mechanics (Smith et al., 2022).

Pedagogically, the implications are substantial. Experiential learning approaches, for instance, have gained prominence, particularly through methods involving real-time demonstrations such as video microscopy. Such interventions help students form spatial intuitions while grounding abstract ideas in visual experience. This engagement not only facilitates individualized feedback but also encourages moments of introspection and inquiry. Active learning frameworks of this nature resonate strongly with recent research emphasizing the need for students to critically engage with concepts such as the Boltzmann factor and probability distributions, cornerstones of statistical mechanics (Danielsson et al., 2020).

Technological innovation further reshapes the instructional landscape. Models such as the flipped classroom encourage students to acquaint themselves with core content before entering the classroom, thereby reserving face-to-face sessions for deeper discussion and problem solving (Zhou, 2023; Ramadhani & Evans, 2022). Particularly in fields marked by conceptual abstraction, Statistical Physics and Quantum Mechanics among them, this pedagogical architecture allows students to enter the learning environment with preliminary conceptual footholds, reducing cognitive barriers and providing clearer entry points for complex discussions (Zhou, 2023; Danielsson et al., 2020).

These developments collectively prompt reflection on traditional academic structures. Learning, after all, is not merely the accumulation of information but a gradual shaping of conceptual understanding. Within this frame, instructors act less as distributors of content and more as facilitators of intellectual inquiry, helping students cultivate the critical and problem-solving skills needed to negotiate the complexities of Statistical Physics (Smith et al., 2022). A balanced integration of conceptual depth and pedagogical innovation offers a more holistic pathway to sustained engagement and comprehension.

Ultimately, teaching Statistical Physics extends beyond the transmission of knowledge. It involves nurturing sustained cognitive engagement with both the abstract and the applied dimensions of the discipline. By fostering environments that support active participation, critical reasoning, and thoughtful pedagogical refinement, educators can more effectively bridge the gap between intuition and understanding.

In the broader context of contemporary education particularly within the sciences the proliferation of learning resources presents both opportunities and challenges. Students attempting to grasp complex ideas such as entropy now encounter a diverse array of materials, from concise online videos to dense scholarly publications. While this abundance can be advantageous, it may also introduce confusion when materials vary in quality or epistemic framing. As a result, instructors increasingly shoulder the responsibility not only of delivering content but also of guiding students in critically engaging with heterogeneous sources. This evolving role aligns with findings from recent bibliometric studies that highlight the intricate relationship between learning resources and educational outcomes (Raman et al., 2024; Deyanova et al., 2022; Misron et al., 2023), Lunke et al., 2023).

The shift toward digital learning during the COVID-19 pandemic further accelerated these conversations. Students expressed mixed perceptions of online course authenticity and quality, yet many acknowledged the usefulness of such materials within contemporary learning ecosystems (Sawarkar et al., 2020; Misron et al., 2023). These insights underscore both student adaptability and the imperative for instructors to design online experiences that foster trust, coherence, and meaningful engagement. Such demands mirror broader pedagogical concerns regarding the careful evaluation and integration of learning resources (Raman et al., 2024; Ho et al., 2024; Lunke et al., 2023).

These issues cannot be separated from the larger sociocultural and technological contexts in which digital learning unfolds. Research has shown that educational technologies, while promising, can inadvertently perpetuate inequities in access and experience if not critically mediated by educators (Stead et al., 2022; Evans & Kleiger, 2025; Syaifudin et al., 2025). Thus, meaningful integration of technology requires sensitivity not only to instructional innovation but also to equity, accessibility, and empowerment. The complexity of this landscape positions educators at a pivotal point, compelling them to navigate multiple layers of pedagogical, technological, and social considerations.

Within this multifaceted environment, studies of multi-source learning in physics education have gained increasing relevance. The central question is whether the ability to draw from diverse sources of information leads to deeper understanding or, conversely, results in fragmented knowledge structures. The present study engages with this tension by employing both quantitative and qualitative approaches to examine learning processes in Statistical Physics.

A focal point of this investigation is the recognition that conceptual understanding is a nuanced and multilayered construct. Recent research highlights how engagement with particular epistemic practices can promote deeper learning. For example, Lin's systematic review of AI literacy education shows how structured epistemic engagement akin to long-established practices in physics supports meaningful problem-solving and conceptual development (Lin, 2025). Likewise, findings from Nurwulandari and Marfuah demonstrate the effectiveness of problem-based learning in enhancing critical thinking and conceptual mastery (Nurwulandari & Marfuah, 2024).

Collaborative and dialogic approaches also hold significant promise. Perl-Nussbaum et al. emphasize how interdisciplinary argumentation enables students to refine their ideas through negotiation and critique, thereby fostering deeper conceptual construction (Perl-Nussbaum et al., 2023). However, the benefits of multi-source learning are tempered by risks. As Settlage and Southerland note, inconsistencies across sources may overwhelm students or lead to epistemic misalignment, complicating the learning process (Settlage & Southerland, 2019). This concern aligns with work documenting persistent misconceptions in physics and the need for coherent instructional strategies (Rachmawati & Supardi, 2021; Jamaludin & Batlolona, 2021).

The present study therefore seeks to map students' pathways toward understanding, capturing not only their conceptual progress but also the frustrations, uncertainties, and moments of insight that accompany their learning experiences. By integrating qualitative narratives with quantitative measures, the study aims to provide a comprehensive account of student cognition in Statistical Physics. In conclusion, the exploration of multi-source learning foregrounds critical considerations regarding the nature of epistemic practices in physics education. As educators continue to optimize learning environments, acknowledging the complexities of knowledge construction and addressing potential pitfalls associated with fragmented or inconsistent information will remain essential for fostering meaningful and enduring conceptual understanding.

METHODS

Research Design

A convergent-parallel mixed-methods design was employed. Quantitative and qualitative data were gathered over the same instructional period, analyzed separately, and integrated during interpretation. This design reflects the nature of the research questions: conceptual understanding is not entirely numerical, nor entirely narrative, but an interplay of the two.

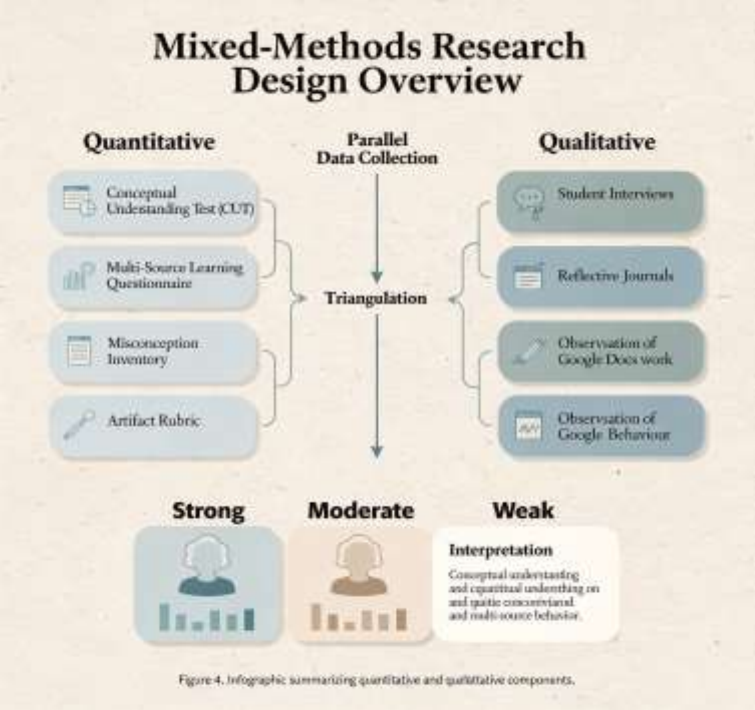

Figure 1. Overview of the mixed-methods design showing parallel quantitative and qualitative data collection, followed by triangulation to produce conceptual understanding profiles.

Participants and Learning Context

The study involved 28 undergraduate physics education students enrolled in a Statistical Physics course. Students completed handwritten assignments and uploaded them via Google Docs, allowing a close look at their reasoning. They naturally engaged with textbooks, online videos, search engines, and AI tools.

Instruments

1. Conceptual Understanding Test (CUT)

Assessed comprehension of entropy, microstate–macrostate relationships, ensembles, probability, and the partition function.

2. Multi-Source Learning Questionnaire

Fourteen Likert items measuring usage of textbooks, YouTube, Google, and AI.

3. Misconception Inventory

Five statements probing well-documented misconceptions.

4. Artifact Analysis Rubric

Evaluated conceptual accuracy, reasoning coherence, representational clarity, source integration, and originality.

5. Qualitative Data

Semi-structured interviews and Reflective learning journals

Data Analysis

Quantitative analysis included descriptive statistics (mean, SD, distribution) and correlation analysis. Qualitative data were coded thematically. Triangulation integrated both strands to generate conceptual understanding profiles: Strong, Moderate, and Weak.

FINDINGS AND DISCUSSION

FINDINGS

The findings of this mixed-methods study are organized into four major areas: (1) students' conceptual understanding of Statistical Physics, (2) their multi-source learning patterns, (3) persistent misconceptions, and (4) qualitative insights into their learning processes. Quantitative data are supported by tables and figures, while qualitative findings draw on interview excerpts and reflective journals.

1. Conceptual Understanding

Students achieved a mean CUT score of 69.6, indicating moderate conceptual understanding, with a range from 52 to 87.

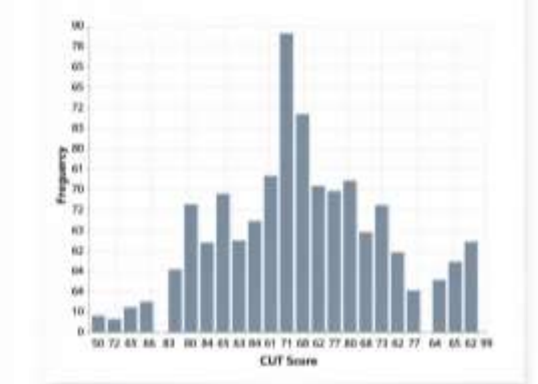

Figure 2. Histogram of CUT Scores

Distribution of students' Conceptual Understanding Test scores, showing clustering in the moderate range. Students with strong scores demonstrated clear connections between mathematical formalism and underlying physical interpretations. In contrast, lower-scoring students tended to recall formulas without anchoring them conceptually.

2. Multi-Source Learning Patterns

Students reported frequent use of: Google (M = 4.18), YouTube (M = 4.07), Textbooks (M = 3.46) and AI tools (M = 2.96)

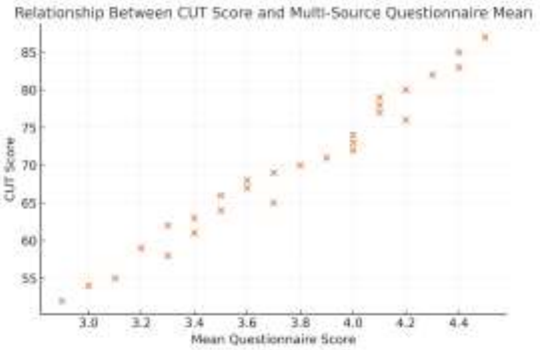

Figure 3. Scatter Plot of CUT vs. Questionnaire Mean

Students using multi-source learning more reflectively tended to score higher on the CUT. The scatter plot shows a clear upward trend: students who actively combined sources performed better. However, students who treated multi-source learning as a series of "quick fixes" often showed shallow understanding.

3. Misconceptions

The average misconception count was 1.9 per student. Entropy, ensembles, and the Maxwell–Boltzmann distribution were the most commonly misunderstood topics.

Table 1. Example Summary of Quantitative Data

ID	CUT	MQ	MC	TB	YT	GG	AI	SP
1	78	4.1	1	4	4	5	3	4
2	65	3.7	2	3	4	4	3	3
3	72	4.0	1	4	5	4	4	4
4	58	3.3	3	3	3	4	2	3
5	83	4.4	1	5	4	5	3	5

Abbreviations:
CUT = Conceptual Understanding Test score
MQ = Mean Questionnaire score
MC = Misconception count
TB = Textbook use
YT = YouTube use
GG = Google use
AI = AI tool use
SP = Self-perceived understanding

Table 2. Sample Misconception Inventory Results

ID	En	P	Es	Eq	MB	Total
1	0	0	0	0	1	1
2	1	0	0	0	1	2
3	0	0	1	0	0	1
4	1	1	0	0	1	3
5	0	0	0	0	1	1

Sample misconception results across five students.
Abbreviations:
MB Distribution = Maxwell–Boltzmann Distribution misconception
En = Entropy
P = Partition Function
Es = Ensemble
Eq = Equal Probability
MB = Maxwell Bolztman

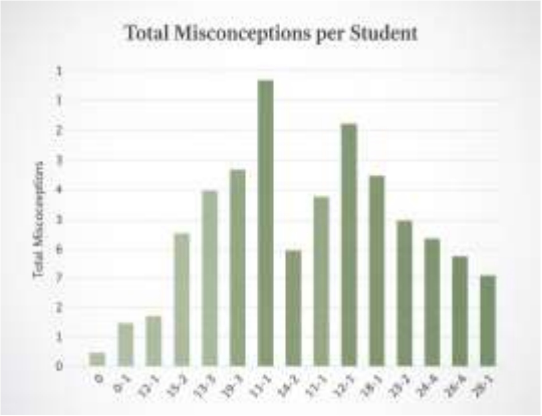

Figure 4. Total Misconceptions per Student

Students with weak conceptual understanding typically scored high on the misconception inventory, confirming that misconceptions function as conceptual barriers even in multi-source environments.

4. Qualitative Insights

While the quantitative results provide a clear picture of how students performed on conceptual tests and how frequently they engaged with various learning sources, the numbers alone do not fully capture how students made sense of Statistical Physics or why certain patterns emerged. To understand these dynamics more deeply, the qualitative data, interviews, reflective journals, and observations from their written artifacts, offer a valuable window into students' reasoning processes. These narratives reveal not only which strategies students used but also the subtle ways in which they navigated confusion, constructed meaning, and negotiated between conflicting explanations. From this qualitative layer, three themes emerged that illuminate the lived experience behind the scores and help explain the variation seen across students' conceptual understanding.

Theme 1: Reflective Integration

High-performing students described an intentional sequence in using sources:

"Book first, then YouTube for intuition, then Google for nuance, then AI for refining understanding."

Theme 2: Persistent Conceptual Bottlenecks

Entropy and the partition function remained elusive even after repeated explanation.

Theme 3: AI as a Dialogic Partner

Students recognized AI as helpful but incomplete:
"It explains well, but I still need the book to see the real structure."

5. Mixed-Methods Triangulation

The integration of quantitative and qualitative findings provides a more complete understanding of students' learning trajectories. When both strands of data were examined together, consistent patterns began to surface patterns that neither method could fully reveal on its own. Through triangulation, three distinct learner profiles emerged, each reflecting a characteristic blend of conceptual performance, misconception levels, and approaches to multi-source learning. These profiles, Strong, Moderate, and Weak, help clarify not only what students understood, but how they approached the learning process and why their conceptual outcomes differed so markedly.

Three profiles emerged: Profile Characteristics

Strong
High CUT, low misconceptions, reflective multi-source learning
Moderate
Inconsistent reasoning, partial misconceptions
Weak
Fragmented source usage, shallow reasoning

Discussion

The results of this study reveal a complex interplay between students' conceptual understanding of Statistical Physics and their engagement with multiple learning sources. The discussion below interprets each major finding through pedagogical and theoretical lenses.

1. Conceptual Understanding Develops Through Coherent Representation-Building

While students' average conceptual understanding was moderate, the variation across individuals highlights the importance of representational coherence. Students with strong CUT scores appeared able to coordinate mathematical formalism with physical intuition. This aligns with existing research showing that Statistical Physics requires students to shift between multiple representational modes. Conversely, lower-performing students often displayed procedural knowledge without conceptual substance. This suggests that conceptual understanding in Statistical Physics is not simply a matter of memorizing formulas or algorithmic steps; rather, it requires a structural grasp of relationships between microstates, macrostates, entropy, and probability.

2. Multi-Source Learning: Helpful Only When Used Reflectively

The positive association between multi-source usage and conceptual performance supports the idea that diverse explanations can scaffold student learning. However, the findings also indicate that not all multi-source engagement is beneficial. Students who used multiple sources superficially, jumping from one explanation to another without deep processing, showed limited conceptual gains. This distinction aligns with theories of self-regulated learning and epistemic agency, which suggest that learners must actively curate, evaluate, and integrate information for it to improve understanding.

3. The Persistence of Misconceptions Indicates Gaps in Conceptual Framing

The prevalence of misconceptions, especially concerning entropy and the partition function, reflects long-standing difficulties documented in physics education research. Even with access to rich explanations online and through AI, these misconceptions remained. This suggests that misconceptions in Statistical Physics are not simply due to lack of information, but rather deep conceptual framing issues. Students often adopt intuitive, but scientifically inaccurate, interpretations that must be explicitly confronted and reconstructed.

4. AI Supports Conceptual Learning, but Cannot Replace Human Sense-Making

The qualitative findings highlight a nuanced relationship between students and AI. Students appreciated AI for its clarity and availability but recognized that it lacked the contextual judgment of a human instructor. Importantly, AI tended to offer explanations that were correct but epistemically "flat", lacking the productive struggle necessary for conceptual change. This implies that while AI can serve as a dialogic partner in learning, it cannot substitute for the interpretive, sense-making processes that characterize meaningful conceptual learning.

5. Triangulated Profiles Reveal Distinct Learning Trajectories

The three conceptual profiles, Strong, Moderate, and Weak, reflect differences not only in performance but in learning behaviors. Strong students engaged in reflective synthesis, moderate students employed partial strategies, and weak students exhibited fragmented and reactive learning patterns. These findings indicate that instructors should differentiate pedagogical interventions: **Strong** students benefit from open conceptual challenges; **Moderate** students need structured prompts that encourage integration; **Weak** students require scaffolding to stabilize foundational concepts.

Overall, the findings suggest that conceptual understanding of Statistical Physics emerges from an active negotiation among representations, explanations, and personal reasoning, rather than from exposure to any single source. Multi-source learning supports this negotiation, but only when approached thoughtfully. Misconceptions persist, AI supplements but does not replace conceptual struggle, and students' profiles reveal the pedagogical importance of guiding interpretive processes.

CONCLUSION

This study highlights that multi-source learning has strong pedagogical potential for supporting conceptual understanding in Statistical Physics. However, the findings emphasize that its success depends on students' ability to synthesize, not merely consume, diverse explanations. Students with strong conceptual understanding showed patterns of reflective integration, while weaker students displayed fragmented or superficial engagement. Misconceptions persist as a major challenge, notably in foundational topics like entropy. AI tools emerged as helpful companions but cannot replace deliberate conceptual reasoning. Educators should therefore provide explicit guidance on how to navigate and integrate multiple learning sources meaningfully.

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