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Interdisciplinary Adaptation of Mathematical Symbols: Mechanisms and Boundaries across Computer Science and Physics

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Abstract

As a key medium for transferring knowledge across disciplines, mathematical symbols do not undergo a direct formal transfer when applied in computer science and physics. Rather than simple reuse, this process involves a structured transformation that includes adjustment of logical rules, extension of symbolic meaning, and alignment with disciplinary environments. Using two representative cases—formal verification in computer science and quantum modeling in theoretical physics—this study applies case analysis and comparative methods to identify three central challenges in the cross-disciplinary adaptation of mathematical symbols: logical conflicts, excessive semantic load, and context-related deviations. Based on these issues, a three-layer adaptation framework of "logical mapping - semantic layering - contextual anchoring" is established. The analysis shows that the limits of symbol adaptation are jointly influenced by the expressive capacity of symbols and the cognitive requirements of the target discipline. The findings indicate that set theory symbols must be integrated with temporal logic operators in concurrent program verification, while linear algebra symbols need to express probability amplitude in quantum state representation. These adaptation processes are restricted by the threshold of semantic density and the value-cost balance of disciplinary needs. The proposed framework is supported by step-by-step comparative analysis and quantitative heuristic boundaries rather than descriptive summarization, which enhances analytical rigor and reusability. The proposed mechanism offers methodological support for the appropriate use of mathematical symbols in interdisciplinary research and contributes to the development of mathematical semiotics and interdisciplinary integration theory.

Keywords

Mathematical Symbols, Interdisciplinary Migration, Adaptation Mechanism, Formal Verification, Quantum Modeling, Application Boundaries

1. Introduction

1.1. Research Background

As interdisciplinary research becomes an increasing trend in the scientific community, mathematical symbols have shifted from tools limited to mathematics to "knowledge bridges" linking disciplines such as computer science, physics, and economics [1]. In computer science, set theory symbols and Boolean algebra symbols are extensively applied in program formal verification, offering logical guarantees for software reliability [2]. In theoretical physics, linear algebra symbols and matrix symbols, once adjusted, serve as fundamental tools for describing complex physical phenomena including quantum superposition and quantum entanglement [3]. Nevertheless, the cross-disciplinary transfer of mathematical symbols frequently faces hidden conflicts. For instance, when Kim *et al.* used group theory symbols in quantum algorithm design in 2022, they overlooked differences in rules of operation priority between mathematics and physics, which caused systematic errors in model validation [4]. In a 2023 investigation on formal verification, the broadening of Boolean algebra semantics caused symbols to hold dual meanings of logical decision and data state, creating confusion in reasoning [5]. These examples imply that cross-disciplinary use of mathematical symbols is not a direct and effortless process. It involves adaptation related to logical structure, semantic content, and disciplinary context. However, structured research on this topic remains limited.

1.2. Research Significance

Theoretically, this study breaks through the traditional view that mathematical symbols are merely formal tools and regards the interdisciplinary migration of symbols as a micro-process of knowledge integration, providing new empirical support for the theory of symbols and knowledge construction in the philosophy of science [6]. Practically, the specific solutions proposed for symbol adaptation problems in computer science and physics can reduce deviations in interdisciplinary applications and provide methodological references for academic research and engineering practice in related fields [7]. In addition, a unified and standardized mathematical symbol adaptation model can improve the efficiency of interdisciplinary collaboration, meeting the current demand for standardization in international academic communities [8].

1.3. Literature Review

Existing studies mainly focus on two dimensions. One is research on the internal logic of mathematical symbols. Frege's theory of symbol reference and Tarski's semantic theory have laid a rigorous foundation for mathematical symbols, emphasizing symbolic consistency within mathematical systems [9] [10]. The other is descriptive research on interdisciplinary application, such as the instrumental use of symbols in the computer field and the contextual transformation of symbols in the physics field [11] [12]. However, existing studies lack systematic analysis of the interdisciplinary symbol migration process and fail to reveal the interactive adaptation mechanism of logic, semantics, and context. Most relevant studies remain at the level of phenomenological description and do not form a reusable adaptation framework [13]. Some symbol conflict resolution models can only address isolated problems and cannot cover adaptation needs at semantic and contextual levels [14], which is the entry point of this paper.

1.4. Research Methods and Structure

This paper adopts a research method combining case analysis and theoretical construction. Case-selection criteria: 1) Typicality: the case represents a mainstream paradigm in computer science or physics; 2) Symbol dependency: the case relies heavily on mathematical symbols for modeling and reasoning; 3) Contrastiveness: the two cases differ significantly in logical rules and semantic requirements to support comparative analysis; 4) Documentation: symbol usage is well-documented and replicable. Formal verification and quantum modeling fully meet these criteria.

Framework derivation steps:

Step 1: Extract core mathematical symbols in each case (set-theory symbols in formal verification; linear-algebra symbols in quantum modeling).

Step 2: Identify logical, semantic, and contextual conflicts in each case.

Step 3: Classify conflicts into three dimensions and compare patterns across cases.

Step 4: Generalize common adaptation mechanisms to form a three-layer framework.

Step 5: Verify and refine the framework using both cases.

It selects formal verification in computer science and quantum modeling in physics as typical cases, deconstructs the migration process of set theory symbols and linear algebra symbols, and extracts adaptation rules. Combined with symbolic epistemology and interdisciplinary integration theory, it constructs an interdisciplinary adaptation framework for mathematical symbols. The structure of the paper is as follows: Section 2 analyzes core contradictions in symbol migration; Section 3 constructs a three-dimensional adaptation mechanism and conducts case verification; Section 4 defines the boundaries of symbol adaptation; Section 5 summarizes conclusions and suggests future research directions.

2. Core Contradictions in the Interdisciplinary Migration of Mathematical Symbols

When mathematical symbols migrate from the mathematical context to target contexts such as computer science and physics, their original logical rules and semantic connotations collide with the knowledge structures and cognitive needs of the target disciplines, resulting in three core contradictions.

2.1. Logical Consistency Conflicts

Mathematical symbols have strict operational closure within their original discipline. For example, the intersection (∩) and union (∪) symbols in set theory follow commutativity and associativity, and their results remain within the conceptual category of set theory [15]. However, when these symbols migrate to the formal verification of concurrent programs in computer science, the dynamic needs of the target field break this closure. In verification, set symbols describe sets of process states, and the dynamic nature of software requires symbols to carry temporal information. Therefore, static intersection symbols must be combined with temporal logic operators ($\square$, $\diamond$) [16]. The atemporality of set operations and the temporality of process states cannot be directly reconciled, leading to logical fractures. This was the core reason for state misjudgment in a 2023 verification study [5]. Essentially, this conflict stems from the tension between the logical completeness of the original discipline and the special logical needs of the target discipline.

2.2. Semantic Overload

The semantics of mathematical symbols are univocal and precise. The semantics of the "vector $\boldsymbol{v}$" in linear algebra are clear, representing a mathematical object with both magnitude and direction [17]. However, when this symbol migrates to quantum modeling in physics, its semantic connotation expands significantly: $\boldsymbol{v}$ must retain its original mathematical properties while also carrying physical semantics such as probability amplitude and observation collapse [4]. The semantic load exceeds the original expressive range, forming semantic overload. Semantic deviation also occurs. The vector space in mathematics is infinitely divisible, while Hilbert space in quantum mechanics, although derived from vector space theory, is constrained by quantum discreteness and is not fully divisible at the physical level [18]. If researchers still interpret $\boldsymbol{v}$ from a purely mathematical perspective, deviations in model interpretation arise.

Semantic overload mainly stems from multilayered semantic attachment to mathematical structures, especially in linear algebra and quantum modeling. In contrast, contextual deviation does not come from semantic expansion but from domain-specific usage constraints imposed by different disciplinary scenarios. To clarify this distinction, the following section analyzes contextual deviation using typical computer-science notation.

2.3. Context-Dependent Deviations

Mathematical symbols are abstract and independent of specific scenarios. The "derivative $\frac{\mathrm{d}y}{\mathrm{d}x}$" in calculus represents the rate of change of a function with respect to an independent variable [19]. However, in algorithm complexity analysis in computer science and motion analysis in physics, this symbol is constrained by different contexts. In algorithm analysis, $\frac{\mathrm{d}y}{\mathrm{d}x}$ must be non-negative because time and computation both show positive growth. In decelerated motion in physics, $\frac{\mathrm{d}y}{\mathrm{d}x}$ is often negative, representing decreasing velocity [20]. Ignoring such constraints leads to errors. For example, applying derivative symbols suitable for uniform motion to variable-speed motion produces conclusions that violate physical laws.

The asymptotic notation $O\left(g\left(n\right)\right)$ in computer science represents an upper bound on the growth rate of algorithm time or space complexity. In pure mathematics, $O\left(\cdot\right)$ can be defined over real-valued or oscillatory functions. In computer science, $O\left(g\left(n\right)\right)$ is strictly non-negative and monotonic because time cost and input size only increase. This contextual constraint means $O\left(\cdot\right)$ cannot be directly transplanted without qualification. Ignoring such constraints leads to errors in complexity judgment and algorithm design. This example is context-specific to computer science, not a universal rule for all mathematical symbols.

3. Construction of the Interdisciplinary Adaptation Mechanism for Mathematical Symbols

To address the above contradictions, and considering disciplinary characteristics in computer science and physics, a three-dimensional adaptation mechanism of logical mapping, semantic stratification, and contextual anchoring is constructed to resolve symbol migration conflicts in a hierarchical manner.

3.1. Logical Adaptation: Construction of Mapping between Original Rules and Target Rules

The main aim of logical adaptation is to handle incompatibilities between symbol operation rules. A rule mapping table is used to clarify which rules should be kept, modified, or supplemented. The procedure includes three steps. First, rule extraction: identify the essential logical rules of symbols in the original discipline to create a list of basic rules. For example, when examining the migration of the set theory symbol “$\cap$” to formal verification, core rules such as commutativity ($A\cap B=B\cap A$) and associativity ($\left(A\cap B\right)\cap C=A\cap\left(B\cap C\right)$) [15] are extracted. Second, rule requirement analysis: develop a set of target rules based on the needs of the receiving discipline. In concurrent program verification, “$\cap$” must represent the intersection of process states, and the required rules include static intersection and dynamic intersection under temporal constraints [16]. Third, rule mapping and adaptation: retain compatible rules like commutativity, convert static intersection into a time-dependent form ($A\cap_t B$, where t denotes the time index), and add rules for checking state consistency [5]. Through this logical adaptation process, set theory symbols achieve compatibility with temporal logic operators and help prevent state misjudgment during verification.

3.2. Semantic Adaptation: Hierarchical Definition of Core Semantics and Extended Semantics

Semantic adaptation addresses the issues of excessive semantic load and deviation by separating semantics into core and extended layers and defining clear boundaries. Step 1: retain core semantics. Preserve the fundamental meaning of symbols from the original discipline to maintain a reliable mathematical basis for interdisciplinary use. For example, in quantum modeling, the vector symbol $\boldsymbol{v}$ must retain its basic attributes of magnitude and direction, which supports the connection between mathematical and physical knowledge [7]. Step 2: define extended semantics. Add discipline-specific meanings that meet the requirements of the target field and clarify their link to core semantics. In quantum modeling, extended semantics for $\boldsymbol{v}$ include probability amplitude (the square of the modulus of $\boldsymbol{v}$ corresponds to the probability of a quantum state occurring) and observation collapse (where $\boldsymbol{v}$ collapses to an eigenstate after observation) [4]. Step 3: semantic consistency check. Ensure that the added semantics do not contradict the core meaning. For instance, probability amplitude must satisfy the requirement that the sum of squared moduli equals 1, maintaining consistency with the mathematical properties of vectors [18]. If this semantic adaptation approach had been applied, model deviations in quantum algorithm development could have been avoided [4].

3.3. Contextual Adaptation: Anchoring Association between Scenario Constraints and Symbol Usage

Contextual adaptation translates implicit constraints of the target discipline into explicit usage rules by analyzing these constraints. The procedure follows three steps:

First, extract contextual constraints. Identify the implicit requirements of symbols in the given scenario through literature and expert consultation. In algorithm complexity analysis, constraints on the derivative symbol $\frac{\mathrm{d}y}{\mathrm{d}x}$ include non-negativity and monotonicity [20]. In physics, motion analysis requires attention to dimensional consistency and the interpretation of positive and negative values [19]. Second, constraint-symbol mapping: convert implicit constraints into explicit usage rules. For example, specify that $\frac{\mathrm{d}y}{\mathrm{d}x} \geq 0$ in algorithm analysis and note that it applies only to the evaluation of positively growing computational processes [20].

Third, scenario adaptation verification: test whether symbol usage complies with contextual rules in specific cases. If $\frac{\mathrm{d}y}{\mathrm{d}x} < 0$ appears in algorithm analysis, it is necessary to determine whether the case reflects abnormal decay or whether symbol application should be adjusted [21]. Formal expression: Let $C = c_1, c_2, \cdots, c_n$ be contextual constraints, S be a symbol, and $F : C \times S \to R$ be a rule mapping. Contextual adaptation holds iff $F(C,S) \vdash valid(S)$.

4. Definition of the Boundaries for the Interdisciplinary Application of Mathematical Symbols

The interdisciplinary adaptation of mathematical symbols is not unlimited. Its boundaries are jointly determined by the expressive capacity of symbols and the cognitive needs of the target discipline. The balance between the two defines the feasible scope of adaptation.

4.1. Boundary of Symbol Expressive Capacity

There is an upper limit to the expressive capacity of mathematical symbols. The combined load of core and extended semantics cannot exceed their threshold. For example, the matrix symbol M represents two-dimensional numerical arrays, which can be reasonably extended to 2 - 3 extended semantics such as linear transformation operators and data feature matrices [22]. However, when required to carry more than 5 extended semantics, such as quantum superposition, input-output structure, and neural network weights, semantic boundaries become blurred, causing ambiguity [23]. The boundary can be quantified by the semantic density index:

$$\text{semantic density} = \frac{\text{number of extended semantics}}{\text{original expressive capacity}} .$$

According to Zheng & Wang (2023), empirical analysis shows that semantic density 1.5 leads to a significant increase in ambiguity. This threshold is heuristic rather than definitive, as it is derived from observational data.

At this point, symbol combination (such as M_{quantum}, M_{economic}) or new symbol creation is necessary [24].

4.2. Boundary of Disciplinary Cognitive Needs

The cognitive needs of the target discipline should be balanced with adaptation cost. The adaptation cost includes time and resources needed for rule transformation, semantic definition, and contextual anchoring [25]. When the cost exceeds the research value, adaptation becomes meaningless. For example, in basic algorithm teaching, only simple arithmetic symbols are needed. If complex topology symbols are introduced, the adaptation cost is high, and the value is limited [26]. The boundary can be evaluated through the value-cost ratio:

$$\text{value-cost ratio} = \frac{\text{value of adaptation}}{\text{cost of adaptation}}$$

Following Özaydın & Arslan (2022), a value-cost ratio 1.2 indicates net benefit. This threshold is heuristic and context-dependent, not an absolute mathematical bound. In quantum computing research, the adaptation value of linear algebra symbols is much higher than the cost, so adaptation is necessary [27].

5. Conclusions and Prospects

5.1. Research Conclusions

Taking computer science and physics as research contexts, this paper analyzes core contradictions in the interdisciplinary migration of mathematical symbols, constructs a three-dimensional adaptation mechanism, and defines application boundaries. The interdisciplinary migration of symbols involves the adaptation of logical rules, the reconstruction of semantic connotations, and contextual anchoring. The core contradictions are logical consistency conflicts, semantic overload, and context-dependent deviations. The mechanism of logical mapping, semantic stratification, and contextual anchoring can effectively address these contradictions. Cases such as the temporal adaptation of set theory symbols and the semantic expansion of vector symbols have demonstrated its practicality. The boundaries of adaptation are determined by expressive capacity and cognitive needs. Under the heuristic thresholds: when semantic density 1.5 or value-cost ratio < 1.2, adaptation is not feasible.

5.2. Research Limitations and Prospects

This study mainly focuses on computer science and physics, and insufficient attention is paid to the adaptation of mathematical symbols in the humanities and social sciences. Future research can expand in two directions: first, expand case studies to fields such as sociology and linguistics, such as contextual constraints in social network analysis and semantic reconstruction in language modeling; second, deepen research on collaborative adaptation mechanisms of symbol systems, analyze logical and semantic linkages during joint migration, and develop automated tools for adaptation with artificial intelligence technology [28]. As micro-carriers of interdisciplinary knowledge integration, the study of symbol adaptation rules will continue to promote the standardization and efficiency of interdisciplinary research.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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