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Article

Multi-Level Constraint Recursive Realization: An Inter-Level Integrative Framework from Physics to Society

A Unified Model Based on Meta-Constraints, System-Environment Conflict, and Recursive Evolution

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Abstract

Understanding the continuity from physical and biological systems to the mind and society remains a fundamental scientific challenge, often hindered by disciplinary fragmentation. This paper proposes the Multi-level Constraint Recursive Realization (MCRR) framework to offer a unified, first-principles-based account of this continuity. Its core thesis is that any persistent dissipative structure must satisfy three irreducible meta-constraints: (1) acquiring resources, (2) optimizing internal processes, and (3) maintaining its boundary. The framework's central mechanism is "recursive realization": higher-order complexities (e.g., adaptive behavior, mind, institutions) are not emergent novelties but strategic solutions evolved to resolve escalating conflicts among these constraints in variable environments. This process is driven by system-environment conflict, follows a logic of dynamic multi-dimensional prioritization, and is governed by cost-benefit trade-offs. MCRR systematically derives a functional hierarchy from passive structures to institutionalized society, explaining increasing flexibility as a recursive response to more complex constraint conflicts. It integrates and extends insights from autopoiesis, life history theory, and active inference, positioning them within the broader narrative of constraint satisfaction. As a heuristic meta-framework, the MCRR provides novel and testable perspectives for cognitive neuroscience, computational psychiatry, AI, and social sciences, fostering interdisciplinary dialogue on adaptation, complexity, and the origins of intelligence and culture.

Keywords: multi-level constraint recursive realization (MCRR); complex systems; autopoiesis; life history theory; dynamic trade-offs; environmental variability

1. Introduction

1.1. Research Background and Challenges

Understanding the continuity from physical structures, living systems, and mental activities to social institutions is one of the core challenges facing modern science. Although reductionist approaches have achieved great success in specific disciplines, they fall short in constructing coherent and functionally consistent explanatory frameworks that span these fundamentally different levels. Physics, biology, cognitive science, and social sciences have each developed sophisticated models and terminologies; however, the conceptual gaps between them make it difficult to form a unified, first-principles-based narrative. This fragmentation limits our fundamental understanding of the nature of its complexity, adaptability, and intelligence.

1.2. Core Thesis: From Existential Constraints to Recursive Realization

This study proposes the "Multi-level Constraint Recursive Realization" (MCRR) framework to address the aforementioned challenge. Our theoretical starting point is a fundamental assertion from

non-equilibrium physics: for any dissipative structure to persist over time, it must continuously satisfy a set of "hard" constraints that keep it from thermodynamic equilibrium. Recent research suggests that complex systems such as life can be viewed as inevitable outcomes of satisfying specific non-equilibrium constraints (England, 2020). The MCRR framework generalizes this concept. Through an analysis of logical necessity, we deduce that any system intending to persist over a timescale t must simultaneously satisfy three logically irreducible meta-constraints: (1) acquiring resources (input) from the environment; (2) optimizing internal processes to reduce the cost of persistence (throughput); and (3) maintaining the boundary and internal structure that define its identity. These three constitute the absolute necessary conditions for a system's existence; violating any one will lead to the system's dissipation or disintegration.

The core innovation of this framework lies in the principle of "recursive realization." We argue that higher-level complexities—such as adaptive behavior, mental phenomena, and cultural institutions—are not accidental or mysterious emergences. Rather, they are "strategic solutions" recursively evolved by systems to cope with increasingly complex and variable environmental challenges. Their fundamental purpose is to satisfy the aforementioned three meta-constraints more robustly, efficiently, or adaptively. The primary driving force for this process stems from "system-environment constraint conflict": when environmental fluctuations, competition, or feedback generated by the system's own activities render strategies at the current level insufficient to effectively reconcile conflicts between constraints, strong selective pressure arises. This pressure favors system variants capable of developing more complex "conflict arbitration and priority ranking" capabilities.

1.3. Theoretical Positioning: A Relational and Processual Perspective

The MCRR framework adopts a thoroughly relational and processual ontological approach. It does not presuppose a static "system" entity separate from the environment. Instead, it views the so-called "system" as a "dynamic pattern" identified within a dynamic network of interactions, distinguished by its ability to continuously execute specific processes that satisfy the three meta-constraints. The essence of a dissipative structure lies in its capacity to localize the capture, storage, and directional release of environmental energy flows more effectively than a mere discrete collection of components. Therefore, the system is the process, and existence is the ongoing satisfaction of constraints.

This perspective resonates deeply with second-order cybernetics and autopoietic theory, emphasizing the observer (or perceiver-actor) as internal to the system and the co-constitutive relationship between the system and its environment. Level transitions (e.g., from fixed behavioral tendencies to an evaluative mind) are functionally necessary solutions to specific, complex environmental challenges. However, their concrete historical realizations are multiple and contingent, following the principle of "multiple realizability." Simultaneously, this framework explicitly emphasizes that the evolution of complexity is not inevitable; it strictly follows an ecological-economic cost-benefit logic: it is an expensive but necessary "insurance premium" paid against "environmental variability." In stable environments, simple and low-cost strategies are optimal.

2. The MCRR Core Theoretical Framework

2.1. Meta-Constraints: The Irreducible Dimensions of System Persistence

Any system attempting to maintain a non-equilibrium state over a timescale t must continuously address the following three fundamental problems. The MCRR framework distills these into three logically irreducible meta-constraints, which together constitute the "hard boundary conditions" for a system's existence.

2.1.1 Resource Acquisition Constraint: Within timescale t , the system must maintain a sustained positive net flow of negentropy (typically manifested as energy or matter) from environment E into system S . This principle is rooted in non-equilibrium thermodynamics; without this external input,

the system will irreversibly tend toward equilibrium according to the second law of thermodynamics, leading to the dissipation of its ordered structure (England, 2020). This constraint defines the input dimensions of persistence.

2.1.2 Internal Process Optimization Constraint: Within timescale t , the internal processes of the system for transforming and utilizing resources must be sufficiently efficient to sustain its operation within a competitive or dissipative environment. The intensity of this constraint is determined by environmental selection pressure, and the underlying trade-off logic has been precisely quantified in life history theory and behavioral ecology (Stearns 1992). For example, an organism's allocation of resources among growth, reproduction, and maintenance is a response to this constraint. This constraint defines the throughput and efficiency dimensions of persistence.

2.1.3 System Boundary and Structural Persistence Constraint: Within timescale t , the system must maintain its boundary, which distinguishes it from the environment, as well as the internal organizational order that supports its specific functions. From a modern information-theoretic perspective, this embodies "individuality"—the information integration of the system as a whole must be higher than the integration of its parts with the environment (Krakauer et al., 2020). The collapse of the boundary or the disordering of the internal structure signifies the end of that system as a specific unity. This constraint defines the identity and integrity dimensions of persistence.

These three constraints are complete and orthogonal (i.e., irreducible). Completeness means that long-term persistence must simultaneously satisfy all three (albeit to varying degrees); satisfying only two cannot be sustained. Orthogonality means that each point to a distinct failure mode: efficient internal specialization cannot compensate for a cutoff of resource input; abundant resources cannot save a collapsing internal structure; and a stable structure without resource input and internal processes is merely a static "dead" structure, not a dynamically maintained dissipative system. Together, they constitute a three-dimensional analytical space for any persistent system: Input, Throughput, Boundary.

Interdisciplinary Corroboration and Universality: This triadic constraint structure reappears in various disciplines under different terminologies, providing inductive support for its role as a foundational analytical dimension. For example:

The core analytical framework in economics and finance is "return, risk, cost (liquidity)."

Strategic management focuses on "growth (market acquisition), efficiency (internal optimization), core competencies (organizational moat)."

Ecology studies "productivity (input), material cycling efficiency (throughput), resilience and diversity (system stability)."

The MCRR framework traces this pattern back to its physical origins, thereby providing a unified ontological foundation for disparate disciplinary insights.

2.2. Recursive Realization: The Dynamics and Mechanism of Level Transitions

"Recursive realization" is the core explanatory principle of the MCRR framework. It refers to the process whereby a system, in order to satisfy the meta-constraints more robustly within a complex and variable environment, recursively evolves more complex strategies or structures, which then become platforms for addressing new challenges. This process is not a teleological ascent but an adaptive evolution driven by "system-environment constraint conflict" and is governed by cost-benefit logic.

2.2.1. Core Driving Force: System-Environment Constraint Conflict

The fundamental driving force of evolution does not stem from an abstract internal "desire for progress" within the system but arises from direct conflicts between its current strategies for satisfying the meta-constraints and the real, variable environment. For example, when the behavior of "acquiring resources" (moving toward food) conflicts spatiotemporally with the need to "maintain persistence" (avoiding a predator), fixed, rigid behavioral patterns become ineffective. Such conflicts constitute a powerful selection pressure.

2.2.2. Basic Algorithm: Dynamic Multi-Dimensional Priority Ranking

Conflict resolution requires a mechanism for real-time arbitration among competing demands. Its computational core is a dynamic priority ranking based on a multidimensional comparison (which can be simplified as "comparing magnitudes"). This operation is ubiquitous across system levels, from a bacterium comparing chemical concentration gradients to decide its swimming direction, to an animal evaluating risk and reward based on neural signals, to humans comparing different goods via monetary prices. The essence of the mind is precisely the complex implementation of this comparative operation within multi-level recursive value spaces.

2.2.3. The Spectrum of Environmental Variability and Cost-Benefit Logic

The evolution of complexity follows strict economic rules. In stable, predictable environments, maintaining complex information-processing architectures (such as nervous systems) is costly, with limited benefits, making "simple-hardwired" strategies the optimal solution (e.g., chemosynthetic organisms at deep-sea hydrothermal vents). Environmental variability (fluctuation frequency, amplitude, and unpredictability) is the ultimate reason driving the "investment" in complexity. Evolution "selects" more flexible, more prospective priority-ranking solutions— that is, more complex ones—only when environmental challenges exceed the problem-solving capacity of existing simple strategies. Therefore, the MCRR levels represent a spectrum of adaptive strategies for coping with different intensities of environmental variability.

2.2.4. "Stress Lines" and Self-Generated New Challenges

The acquisition of new capabilities (e.g., stronger cognitive abilities) enhances a system's adaptability, allowing it to exploit new niches, form larger populations, or build more complex social structures. However, this simultaneously generates new "stress lines": intensified within-population competition (social pressure) and increased environmental diversity (cognitive pressure). These new challenges, derived from the system's success, become sources for the next round of constraint conflicts, potentially driving further complexification. This is an endogenous cycle of "solving conflicts → enhancing capabilities → encountering new conflicts."

2.3. Functional Hierarchy: A Spectrum Based on Strategic Complexity

Based on the principle of recursive realization, we can outline a functional hierarchy spectrum from passive to active and simple to complex. Each level represents a typical class of strategies for solving the meta-constraints, with higher levels formed by incorporating lower-level strategies as components and adding new coordination and control mechanisms to them.

2.3.1. Level 0: Passive Structural Layer (e.g., Vortices, Chemical Waves)

Strategy: This relies entirely on sustained, specific external condition flows (e.g., temperature gradients and concentration gradients) to passively and coincidentally satisfy the meta-constraints.

Characteristics: No active regulatory mechanisms were observed. Changes in conditions lead to constraint violations and structural dissipation.

2.3.2. Level I: Autopoietic Layer (e.g., Protocells, Cells)

Strategy: Achieve operational closure by continuously producing and maintaining their own boundaries and components through an internal process network (metabolism).

Transition Significance: Transforms constraint satisfaction from "dependent on external coincidence" to "actively realized by internal organization." The meta-constraints are internalized: resource acquisition → assimilation, process optimization → metabolic network cycles, and system persistence → self-produced boundary. This is the minimal definition of life (Thompson 2007).

2.3.3. Level II: Adaptive Tendency Layer (e.g., Bacteria, Plants)

Strategy: Builds upon autopoiesis, evolving fixed, naturally selected directional behaviors, or physiological regulation patterns (e.g., chemotaxis and phototropism).

Characteristics: Enables direct, reflexive responses to specific environmental features, thereby expanding the capacity to maintain constraints in variable environments.

2.3.4. Level III: Evaluative Mind Layer (e.g., Animals with Central Nervous Systems)

Strategy: When environmental complexity leads to frequent conflicts among fixed tendencies (e.g., conflict between approach and avoidance), an internal mechanism for valuing and selecting behaviors (i.e., the mind) evolves.

Mind as a Multi-Constraint Computational System:

Interoceptive System: Monitors deviations in physiological states (e.g., energy deficit), converts them into feelings (e.g., hunger), and provides a real-time evaluation of "optimization" and "persistence" states.

Emotional System: Through learning, associates situational cues with potential major gains or losses, generating motivational states (e.g., fear and desire) and enabling prospective valuation of future "acquisition" opportunities and "persistence" threats.

Executive Control System (e.g., prefrontal cortex): Integrates multi-source value signals, performs cross-temporal/spatial, multi-objective trade-off comparisons, conflict resolution, and planning, and achieves dynamic multi-objective optimization.

Functional Manifestations: Curiosity (valuation of information acquisition), habits (optimization of cognitive effort), and anxiety (ongoing threat monitoring) are all functional expressions of this computational system.

2.3.5. Level IV: Institutionalization Layer (Human Societies)

Driving Force: To reduce the costs of complex value games among individuals and address intergenerational continuity, part of the computation is externalized and objectified into shared symbols and rule systems.

Strategy: Institutions as externalized solutions for satisfying meta-constraints at the societal level

Acquisition Constraint → Currency, markets (externalized valuation and exchange protocols).

Optimization Constraint → Tools, technology, law (externalized efficiency enhancement and coordination rules).

Persistence Constraint → Morality, ideology, and national identity (internalized norms and identity construction at the group level).

This hierarchical spectrum is functional rather than strictly taxonomic. It depicts how strategies for satisfying meta-constraints recursively evolve toward greater flexibility and cognitive depth in response to increasing environmental and social complexity.

3. Systematic Dialogue with Related Theories

The MCRR framework does not arise in a vacuum; rather, it is rooted in and aims to integrate several important scientific theoretical traditions. This section systematically elaborates on the dialogic relationship between the MCRR and autopoietic theory, life history theory, active inference/free energy principle, and second-order cybernetics, clarifying their complementarity, mutual deepening, and extension.

3.1. Relationship with Autopoietic Theory: Foundation, Starting Point, and Beyond

Autopoietic theory is a crucial cornerstone of the MCRR framework. The MCRR fully adopts and internalizes the strict definition of the minimal living unit in autopoietic theory: a system that achieves operational closure by continuously producing and maintaining its own boundary and components through its internal process network (Thompson, 2007). In the MCRR hierarchical

spectrum, this is explicitly designated as Level I: the Autopoietic Layer, the logical starting point of life's complexity.

The MCRR framework deepens and extends the insights of autopoietic theory in two key ways.

Providing a Physical and Evolutionary Context: Autopoietic theory elegantly describes what life is (its organizational form), but its discussion of why it must be so and from where it comes is relatively less emphasized. Through these three meta-constraints, the MCRR provides a more fundamental physical rationale for the emergence of autopoietic systems: autopoiesis is a highly effective strategic solution for satisfying the three constraints in a long-term, robust manner. It situates the question of the origin of life within the broader physical problem of how dissipative structures satisfy persistence constraints.

Building a Bridge to Higher Complexity: Autopoietic theory primarily focuses on the basal logic of life. Building upon this, MCRR systematically argues, using the "recursive realization" principle, how autopoietic systems serve as a platform for evolving higher-level complexities such as adaptive behavior, mind, and culture. It addresses the question of "what comes after" autopoietic systems.

Relational Positioning: Autopoietic theory is a constitutive part of the MCRR framework concerning the core logic of life; MCRR is the "meta-framework" that places this logic within the grander narrative of constraint satisfaction and recursive evolution from physics to society.

3.2. Relationship with Life History Theory/Behavioral Ecology: Quantification, Instantiation, and Theoretical Grounding

Life history theory and behavioral ecology are core fields in biology that study how organisms allocate limited resources across their lifespan to maximize fitness. The MCRR framework exhibits a profound correspondence and complementarity with this domain.

MCRR views the classic trade-offs in life history theory (e.g., current reproduction vs. future survival, offspring quantity vs. quality) as specific manifestations and quantitative expressions of its triadic meta-constraints within the particular domain of biological survival and reproduction. For example:

Investment in "current reproduction" primarily relates to resource acquisition and transformation (conversion of energy into genetic legacy).

Investment in "future survival" primarily relates to maintenance and repair (satisfying the system persistence constraint).

Any specific life history strategy represents an evolutionarily stable solution reached by an organism through the dynamic prioritization of these three constraints under specific ecological conditions.

The MCRR provides a more universal and fundamental theoretical grounding for these specific biological trade-offs. This suggests that life history trade-offs are not phenomena unique to biology but are manifestations, in the biological realm, of a fundamental mathematical problem that any system attempting to persist under conditions of limited resources and environmental variability must confront. Furthermore, the MCRR's cross-level perspective offers a unified motivational framework for understanding the multi-objective conflicts (not just energy, but also risk, time, and social cost) underlying behaviors such as foraging and risk avoidance.

Relational Positioning: Life history theory/behavioral ecology are excellent, quantifiable "instantiations" of MCRR's constraint logic in the biological domain; MCRR provides a more universal "axiomatic" background for these instantiations.

3.3. Relationship with Active Inference/Free Energy Principle: Complementary Functional Goals and Implementation Algorithms

Active inference (and the free energy principle as its basis) is an ambitious unifying framework that posits that intelligent systems maintain their existence by minimizing the prediction error (or free energy) of their internal models of the world (Friston, 2019). The MCRR shares common ground

with this framework but also has fundamental differences, resulting in a relationship of deep complementarity.

Common Ground: Both start from the basic stance that a system maintains its own organizational integrity and distance from the thermodynamic equilibrium.

Fundamental Differences

Singularity vs. Plurality of Optimization Target: Active inference treats "prediction error minimization" (or variational free energy bound minimization) as a unified, singular optimization target. MCRR insists that resource acquisition, process optimization, and system persistence are three logically incommensurable and often conflicting dimensions. Research in neuroeconomics confirms that decision-making relies on the independent computation and weighted integration of neural systems encoding reward (acquisition), effort cost (optimization), and risk/uncertainty (persistence) (Rangel & Clithero, 2023), aligning better with a multi-objective (Pareto) optimization picture.

Level of Explanation: The MCRR aims to answer the question, "why is a certain optimization mechanism needed?"—because the system must cope with the inherent conflicts among multiple irreducible constraints. Active inference aims to answer the question of "how is a powerful optimization algorithm implemented?"—namely, by guiding perception and action through prediction error minimization.

Relational Positioning: The two relate as problem versus solution and purpose versus means. The MCRR defines the "multi-constraint dynamic trade-off problem" that any persistent intelligent system must solve; active inference provides a powerful "universal algorithm" based on Bayesian inference to approximately solve this problem. The MCRR offers a possible explanation for the origin of the "value" or "preferences" implicit in the "generative model" of active inference—they arise from evaluating the state of meta-constraint satisfaction.

3.4. Relationship with Second-Order Cybernetics and Complex Systems Theory: Epistemological Resonance and Synthesis

The MCRR resonates with and synthesizes the epistemology and methodology of second-order cybernetics and modern complex systems theory.

3.4.1 Second-Order Cybernetics: Emphasizes the inclusion of the observer within the observed system, focusing on circular causality, self-reference, and self-generation. The MCRR fully internalizes this perspective.

Endogeneity of the Observer: In the MCRR, the "mind" (Level III) is precisely the "self-observing and describing subsystem" evolved internally by the system. This subsystem constructs models of the system's own state and its relationship with the environment and makes decisions based on these models, realizing strict self-referential cycles.

Co-constitution of the System and Environment: MCRR emphasizes that the system continuously alters its environment through its constraint-satisfying actions, and this altered environment, in turn, becomes a new set of constraints. This is a dynamic, evolutionary version of the second-order cybernetic idea that "the observer constructs its world through action."

3.4.2 Complex Systems Theory: The MCRR framework is essentially a theory of the hierarchical structure and evolutionary dynamics of complex systems. It shares with complex systems theory a focus on emergence, adaptability, nonlinearity, and network thinking. The MCRR's contribution lies in providing a coherent narrative for the growth of hierarchical complexity based on first principles (meta-constraints) and a clear driving force (constraint conflict), integrating physical, biological, and social complexity within the same logical chain.

Relational Positioning: MCRR can be viewed as a synthetic attempt to systematically apply the epistemological insights of second-order cybernetics and the dynamic insights of complex systems theory to understand biological and social evolution across spatiotemporal scales. It provides a set of concrete conceptual tools (meta-constraints, recursive realization) for analyzing how complexity is recursively generated and maintained within self-referential and co-constitutive cycles of the social world.

4. Theoretical Implications, Application Prospects, and Testable Propositions

The MCRR framework is not merely a metaphysical theoretical construct; it aims to provide a heuristic and actionable research program across multiple disciplines. This section elaborates on its theoretical value, outlines its application prospects in several key fields, and deduces a series of scientifically testable propositions based on its core logic.

4.1. Theoretical Value

The core theoretical contributions of the MCRR framework lie in its integrative nature, foundational characteristics, and heuristic power.

4.1.1 Providing a Unified Explanatory Logic Across Levels: MCRR bridges the conceptual gaps between physical systems and social phenomena, offering a coherent narrative starting from the basic physical fact of "constraint satisfaction" to civilizational institutions. This first-principles-based integration aligns with the interdisciplinary research direction advocated by modern complex systems science (Mitchell 2021).

4.1.2 Establishing a Richer Naturalistic Motivational Foundation: Compared to models with a singular optimization target (such as pure utility maximization or prediction error minimization), the MCRR explicitly places multiple, incommensurable, and often conflicting constraints at its core. This aligns more closely with the multi-motivation, multi-system decision-making models increasingly recognized in psychology and economics (Crockett, 2023), providing a firmer naturalistic grounding for understanding the inherent tensions, contradictions, and failures of self-control in behavior and decision making.

4.1.3 Clarifying the Functional Nature of Complexity: By positioning different levels of system properties (e.g., autopoiesis, emotion, institutions) as recursive solutions to constraint conflicts of specific complexity, MCRR helps clarify the core functions of these complex traits and the reasons for their emergence in evolution.

4.2. Application Prospects

The MCRR framework can guide new research paradigms and model building in several fields.

4.2.1 Cognitive Neuroscience: MCRR predicts that decision-making does not stem from a singular "reward" or "error" signal but from the parallel computation and competitive integration of multiple neural systems respectively encoding "expected gain/opportunity" (acquisition), "subjective effort/cost" (optimization), and "risk/uncertainty/social threat" (persistence). This can guide research to explore the independent representation of these value dimensions in the brain (e.g., the nucleus accumbens, anterior cingulate cortex, amygdala, and insula) and their integration mechanisms in the prefrontal cortex (Lockwood & Klein-Flügge, 2023). This shifts decision-making research from seeking a common currency to understanding the dynamic trade-offs of multi-dimensional value.

4.2.2 Computational Psychiatry: MCRR supports the reconceptualization of mental disorders as specific dysfunctions or imbalances within the multi-constraint value computation system. For example:

Addiction: Could be viewed as the hyperactivity and dominance of the "acquisition" system (sensitivity to drug or behavioral rewards) relative to a desensitized "optimization" system (insensitivity to long-term costs) and an under-assessing "persistence" system (poor evaluation of risk and threats to self-identity).

Anxiety Disorders: Could be understood as chronic hypersensitivity and dysregulation of the "persistence" system (threat monitoring).

Depression: Might relate to a "paralysis" of the overall value computation system, where the "optimization" system (extremely high valuation of effort cost) and the "persistence" system (pessimism about the future) overwhelmingly suppress the "acquisition" system (anhedonia). This multi-system dysfunction perspective is gaining increasing support (Huys et al. 2022).

Artificial Intelligence: Provides meta-guidance for designing agents with rich, non-reductive intrinsic motivation. The MCRR suggests that to handle multi-objective conflicts in the real world, Artificial General Intelligence (AGI) may need to be endowed with several irreducible basic drives corresponding to the three meta-constraints, rather than a single utility function. This points towards research directions in reinforcement learning that explore structured intrinsic motivation (e.g., balancing curiosity, efficiency, and safety) (Oudeyer & Kaplan, 2023). For instance, an autonomous robot should be endowed with an intrinsic concern for energy efficiency (optimization) and hardware integrity/safety (persistence), in addition to task rewards (acquisition).

Social Sciences: MCRR provides a deep explanatory model for analyzing cultural differences and social institutional changes. Different socio-cultural contexts can be seen as stable equilibria formed by setting different default long-term priorities for the three meta-constraints. For example:

Individualistic Cultures: May default to placing greater emphasis on individual "acquisition" and "optimization" (self-sufficiency, efficiency), while externalizing part of the "persistence" responsibility to institutions.

Collectivistic Cultures: May default to emphasizing group-level "persistence" (harmony, stability, identity), thereby imposing more constraints on individual "acquisition" and "optimization" behaviors (Henrich, 2020).

Institutional change can be interpreted as a collective process of "recursive realization" undertaken by a society to rebalance the three constraints when the social environment (technology, resources, and demographic structure) changes.

4.3. Testable Propositions and Unique Predictions

The core logic of the MCRR framework leads to a series of unique predictions that extend beyond existing theories. These predictions can be empirically tested and used for model comparisons at multiple levels.

4.3.1 Neural Predictions for Inter-Level Conflict Resolution: The MCRR not only predicts the multi-dimensionality of value computation but also predicts that neural subsystems at different levels (e.g., interoception, emotion, executive control) play specific arbitration roles in conflict resolution. A testable hypothesis is that when decisions involve conflicts within the same level (e.g., choosing between two equally valued rewards), they primarily rely on basic sensorimotor and reward evaluation circuits. However, when decisions involve cross-level or cross-dimensional conflicts (e.g., "acquisition-persistence" conflicts involving high reward and high risk, or "acquisition-optimization" conflicts requiring great effort), they will systematically and more strongly recruit brain regions responsible for conflict monitoring and higher-order integration, such as the anterior cingulate cortex and prefrontal cortex. Their activation patterns can be modeled as the dynamic weighting of signals from different constraint violations.

4.3.2 Behavioral Predictions on Environmental Variability Driving Complexity: MCRR's core tenet of MCRR is that environmental variability drives recursive realization. This leads to a testable comparative ethology and cross-cultural prediction: in ecological niches or cultures with objectively higher physical or social environmental variability, individuals' behavioral strategies should universally exhibit higher cognitive flexibility, more future-oriented planning, and a greater preference for learning complex rules. For instance, one could predict that individuals from regions with high climatic variability or historically volatile societies would demonstrate stronger executive functioning, lower delay discount rates, and greater proficiency in handling probabilistic, changing environments in laboratory tasks.

4.3.3 Computational Predictions of Psychopathology as Constraint System Imbalance: MCRR views mental disorders as chronic imbalances in the multi-constraint value computation system. This leads to a quantifiable diagnostic prediction: different categories of mental disorders should correspond to specific, quantifiable "shifts in constraint weighting." For example, by combining behavioral tasks and computational modeling, one could predict and test that decision models of individuals with addiction would show abnormally elevated "acquisition" weighting and

insensitivity to "optimization" (cost); models for individuals with generalized anxiety disorder would show an excessively high baseline gain and difficulty in attenuation for the "persistence" (risk) system; while models for depression might show attenuated overall value signal amplitude and relative dominance of the "optimization" weight. This "constraint signature profile" based on computational modeling could provide new quantitative indicators for the subtyping of mental disorders and treatment responses.

4.3.4 Constraint Priority Hypothesis for Institutional Evolution: MCRR posits that institutions are externalized solutions to societal-level constraints. This generates a macro-level hypothesis for history and the social sciences: major social institutional changes (e.g., from hunter-gatherer societies to agricultural states or the rise of market economies) often occur when the core constraint conflicts faced by a society undergo fundamental transformation. For example, one could analyze and test whether the emergence of the state form is related to situations where, under population pressure, the need for "optimization" (large-scale coordination efficiency) and "persistence" (collective defense) overrides the need for individual "acquisition" flexibility. This hypothesis can be tested by analyzing the relationships between climate, population, resources, and institutional variables in historical datasets.

These propositions demonstrate how the MCRR framework can move from abstract theory to empirical science, undergoing testing, refinement, and enrichment at various levels.

5. Conclusion

This paper proposes the "Multi-level Constraint Recursive Realization" (MCRR) framework as an attempt to construct an interdisciplinary unified theory. Its fundamental aim is to provide a logically coherent, first-principles-based integrative narrative for understanding the continuity from the physical world and living systems to mental activities and sociocultural phenomena.

The framework begins from a concise yet robust physical premise: any dissipative structure that persists in time must continuously satisfy a set of meta-constraints concerning resource input, internal efficiency, and boundary integrity. The logical incommensurability of these three constraints defines the core problem facing persistent systems—namely, a multi-objective optimization problem characterized by intrinsic tensions.

Building on this foundation, the principle of "recursive realization" serves as the core explanatory mechanism. It reveals that observed high-level complexities—from autopoiesis and adaptive behavior to evaluative mind and institutionalized civilization—are neither mysterious emergences nor independent domains. Rather, they constitute a series of strategic solutions recursively generated through evolution as systems respond to increasingly complex and variable environments. The essence of these solutions lies in developing more powerful and flexible dynamic arbitration mechanisms to resolve the inevitable, escalating conflicts that arise from satisfying multiple meta-constraints. This process is driven by the ongoing, constraint-mediated interplay between a system and its self-constructed environment.

The MCRR framework is positioned as heuristic and integrative. It does not seek to replace mature discipline-specific theories (e.g., autopoietic definitions of life, life-history quantifications of trade-offs, or active-inference descriptions of cognitive algorithms). Instead, it aims to provide these scattered yet profound insights with a shared conceptual foundation and a coherent meta-narrative. It clarifies how rules discovered at different levels and in different domains can be understood as recursive realizations of a single fundamental logic: maintaining a non-equilibrium process under multiple, dynamic constraints across varying conditions.

We have outlined the framework's application prospects and testable propositions across multiple disciplines, indicating that MCRR is not merely philosophical speculation but a viable research program capable of engaging in fruitful dialogue with empirical science and engineering practice. Future work should focus on advancing the framework along two paths: first, through formalization and modeling—transforming qualitative descriptions of "constraint conflict" and "recursive realization" into computable models (e.g., agent-based models, multi-objective

reinforcement learning frameworks) for simulation and prediction; second, through empirical refinement—testing and revising specific hypotheses derived from the framework within concrete fields such as neuroscience, psychology, and anthropology.

We hope the MCRR framework can serve as a "conceptual lingua franca" and a heuristic tool to foster interdisciplinary dialogue around core ideas such as "constraints," "adaptation," and "recursive complexity." In an age of increasing knowledge fragmentation, this effort to construct a coherent, holistic understanding may prove fundamentally important for addressing the existential challenges that complexity itself poses to human society and the global ecosystem.

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