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Article

Multi-Level Constraint Recursive Realization (MCRR): A Cross-Level Theoretical Framework Based on Meta-Constraints and Recursive Optimization

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Abstract

This paper proposes the "Multi-level Constraint Recursive Realization" (MCRR) framework, which seeks to provide a logically unified, first-principles-based meta-theoretical model for understanding the continuity spanning physical systems, life, cognition, and socio-cultural phenomena. Its core thesis is that the very existence of any dissipative structure, which intends to persist over time, implies that it must simultaneously and continuously satisfy three absolute meta-constraints that are logically irreducible to one another: (1) acquiring resources from the environment, (2) optimizing internal processes to reduce the cost of persistence, and (3) maintaining the boundary and structural stability that define it as a unified whole. These constraints constitute the "hard boundaries" of a system's existence; violation of any single constraint leads to the system's dissipation or disintegration. Building upon this foundation, the framework constructs a logical hierarchy of systems, ranging from passive physical structures to active autopoietic systems, further to systems with adaptive behavioral tendencies and internal evaluative minds, and ultimately to institutionalized societies. Each higher level can be viewed as a strategic solution, recursively evolved by the system to cope with environmental complexity, aimed at satisfying the underlying meta-constraints more robustly or efficiently. Specifically, we argue that the essence of mind (encompassing sensation, emotion, and cognition) is a dynamic multi-constraint value-computation and optimization system, whose evolution addresses conflicts among basic behavioral tendencies in complex environments. The framework engages in a deep dialogue with theories such as autopoiesis, life history theory, and active inference, thereby providing an analytical tool and conceptual map designed to integrate, not replace, knowledge from existing disciplines.

Keywords: multi-level constraint recursive realization (MCRR); meta-constraints; autopoietic theory; life history theory; dynamic trade-offs; cross-level integration; value computation; complex systems evolution

Methodological Note: During the preparation of this manuscript, the author used large language models (LLM) for language polishing and translation. The author is solely responsible for the entire scientific content, including the conceptualization, theory development, and analysis.

1. Introduction: Towards a Unified Logic for the Continuity of Complex Systems

Bridging the explanatory gaps across physics, life, mind, and society constitutes a central challenge in the science of complex systems. While prevailing reductionist approaches are highly effective at decomposing phenomena, they face limitations in reconstructing coherent, functionally consistent narratives that span these different levels. This paper aims to propose a Multi-level Constraint Recursive Realization (MCRR) analytical framework, providing a unified set of modeling principles for understanding both the continuity and differentiation among systems at various levels.

The logical starting point of the MCRR framework is grounded in a physically indisputable fact: the very persistence over time of any dissipative structure signifies its fulfillment of a set of necessary constraints. Recent research grounded in non-equilibrium physics has provided a firmer theoretical basis for this view, positing that complex systems such as life are necessary manifestations of satisfying specific dissipative constraints (England, 2020). This framework generalizes this idea, deriving—through a rigorous analysis of necessary conditions—three logically irreducible meta-constraints that any system intending to persist must simultaneously satisfy: (1) resource acquisition, (2) internal process optimization, and (3) the persistence of the system's boundary and structure. Together, these constitute the "hard boundaries" of a system's existence; violating any one leads to its dissolution. This concept of a constraint space aligns with modern, information-theoretic perspectives on "individuality" (Krakauer et al., 2020).

The core innovation of the MCRR framework lies in the principle of "recursive realization." It posits that higher-order complexities—such as adaptive behavior, mind, and culture—can be systematically explained as strategic solutions recursively evolved by a system to satisfy the aforementioned fundamental meta-constraints more robustly and efficiently within complex, variable environments. This view of hierarchical progression as a constraint-driven process of strategic complexification provides a clear pathway for formal modeling (Deacon, 2022). The framework contrasts with models that attribute diverse behaviors to a single optimization objective (e.g., prediction error minimization), explicitly proposing an optimization problem based on the dynamic trade-offs among a triad of constraints. This offers meta-guidance for constructing agent models endowed with richer, more authentic motivations.

2. Core Framework: Meta-Constraints, Recursive Realization, and the Hierarchical Architecture

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

The rigor of the MCRR framework begins with the argument for the logical necessity and mutual irreducibility of the three meta-constraints. Consider a dissipative structure S that persists over a time scale τ . Its existence logically entails:

Resource Acquisition Constraint: Over τ , there must be a continuous net flow of negentropy (or equivalently, energy/matter) from the environment E into S . This constraint is rooted in non-equilibrium thermodynamics, and its necessity is further articulated in discussions on the physical foundations of life's origin (England, 2020). If this flow is interrupted or becomes negative, S will tend towards equilibrium according to the second law of thermodynamics, leading to the dissipation of its ordered structure. This constraint concerns input.

Process Optimization Constraint: Over τ , the internal processes of S must be sufficiently efficient to persist amidst competition. The strength of this constraint is determined by environmental selection pressures, and the underlying trade-off logic finds precise quantitative expression in life history theory and behavioral ecology (Stearns, 1992). This constraint concerns internal transformation.

System Persistence Constraint: Over τ , S must maintain the boundary that distinguishes it from the environment, as well as the internal organizational structure that sustains its specific functions. This constraint pertaining to "individuality" can be strictly defined and measured from an information-theoretic perspective in modern systems science (Krakauer et al., 2020). If the boundary disintegrates or the internal structure becomes disordered, S ceases to exist as that specific system. This constraint concerns identity and integrity.

These three elements constitute a complete and orthogonal constraint space:

Completeness: For a system to persist over τ , it must simultaneously (albeit to varying degrees) satisfy all three requirements. No system can persist long-term by satisfying only two.

Orthogonality (Irreducibility): The three point to different aspects of systemic persistence. Efficient processes (satisfying Constraint 2) cannot compensate for a cessation of resource input (violating Constraint 1); abundant resources (satisfying Constraint 1) cannot make up for the collapse

of internal structure (violating Constraint 3); and a stable structure (satisfying Constraint 3), without resource input and effective transformation (violating Constraints 1 & 2), is merely a static "dead" structure, not a dynamically maintained dissipative system. They correspond to three independent analytical dimensions: input, throughput, and boundary.

Absoluteness: These are hard boundary conditions for the continued existence of a system, not soft goals that can be flexibly traded off. In the real world, the degree to which these three constraints are met directly determines the probability of the system's persistence under environmental selection and random perturbations.

2.2. Recursive Realization and Hierarchical Evolution

"Recursive realization" is the core explanatory principle of MCRR: higher-level, more complex system properties or behavioral patterns can be systematically explained as strategic solutions recursively evolved by the system to satisfy the underlying meta-constraints in a more robust, efficient, or environmentally adaptable manner. The ascent of levels can be viewed as a strategic complexification process driven by the system's need to cope with increasing challenges (e.g., environmental fluctuations, resource competition, internal conflicts) in meeting the hard constraints. Accordingly, we outline five logically progressive functional levels:

Level 0: Passive Structure Layer

Examples: Vortices, chemical dissipative structures.

Characteristics: Satisfaction of the three meta-constraints depends entirely on specific, sustained external conditional flows (e.g., temperature gradients, concentration gradients). Constraint satisfaction is passive and coincidental; the system itself lacks any active regulatory mechanisms. Changes in conditions lead to constraint violation and structural dissipation.

Level I: Autopoietic Layer

Examples: Minimal life units (e.g., protocells).

Characteristics: The system, through its internal network of processes, continuously produces and maintains its own boundary and internal components. This represents a fundamental transition: satisfying constraints shifts from "relying on external coincidence" to being "actively realized by internal organization." The meta-constraints are internalized into its operational logic:

Resource Acquisition → Assimilation (selective uptake).

Process Optimization → Network Cycles (self-producing metabolic pathways).

System Persistence → Boundary Generation and Maintenance.

Significance: Adopts autopoietic theory as the minimal definition of life and the starting point of the hierarchy (Thompson, 2007). This level accomplishes a fundamental transition: the meta-constraints are internalized as the logic of its operational closure—metabolic networks realize "process optimization," self-produced boundaries satisfy "system persistence," and selective assimilation addresses "resource acquisition." The system's own existence becomes the immanent, operationally closed "purpose" of its operation.

Level II: Adaptive Tendency Layer

Examples: Bacteria, plants, and other simple life forms.

Characteristics: The intrinsic logic of autopoiesis is expressed externally in variable environments as innate, naturally selected, directional behaviors or physiological regulatory patterns (tropisms like chemotaxis, energy conservation, harm avoidance). This constitutes a direct, reflexive response to the meta-constraints.

Level III: Evaluative Mind Layer

Examples: Animals with central nervous systems.

Argument for Evolutionary Necessity: When environmental complexity leads to frequent and uncertain conflicts between basic behavioral tendencies (e.g., approach vs. avoidance) or between immediate and long-term gains (e.g., exploration vs. rest), fixed reflexive patterns fail. Under these

conditions, some form of internal state evaluation and behavioral selection mechanism is strongly selected for. The nervous system is an excellent evolutionary solution for this mechanism. Modern cognitive neuroscience indicates that decision-making relies on the interaction and competition of distinct neural network systems encoding expected reward (acquisition), subjective effort cost (optimization), and risk/uncertainty (persistence), respectively (Rushworth et al., 2012).

The Mind as a Multi-Constraint Value Computation System:

Interoceptive System: Transduces physiological parameter deviations (e.g., energy deficit, tissue damage) into negative signals (hunger, pain), enabling low-cost, real-time valuation of current "persistence" and "optimization" states.

Emotional System: Based on learning, associates contextual cues with potential significant future gains or losses, generating motivational states (fear, desire) that provide prospective valuation and alertness regarding "acquisition" opportunities and "persistence" threats.

Executive Control System (e.g., prefrontal cortex): Receives and integrates value signals from multiple sources, performing cross-temporal, cross-objective (multi-constraint) weighting comparisons, conflict resolution, and sequential planning to achieve dynamic multi-objective optimization.

Reinterpretation: Phenomena like curiosity (valuation of information acquisition), habits (optimization of cognitive energy expenditure), and anxiety (persistent threat monitoring) are functional manifestations of this computational system.

Level IV: Institutionalization Layer

Examples: Human societies.

Driving Logic: To reduce the complexity and cost of value computation games among individuals and to address the problem of intergenerational continuity, part of the computation is externalized and objectified into shared symbolic and rule systems. Institutions such as money, law, and morality can be viewed as externalized solutions to the three meta-constraints at the societal level, a process consistent with the evolutionary trajectory of human societies as complex adaptive systems (Turchin, 2018).

Manifestations: Money and markets (externalized computation protocols for the acquisition constraint), tools and laws (externalized schemes for the optimization constraint), morality and ideology (internalized norms at the group level for the persistence constraint).

2.3. Clarification on the "Necessity" of Level Transitions

It is crucial to clarify that the transitions from one level to the next, as described by the MCRR framework, represent a functional and logical necessity, not a historical or formal uniqueness. This view aligns with the "functionalist" explanatory framework in evolutionary theory, where specific environmental challenges create strong selection pressure for a particular function, but the concrete form realizing that function (the "realizer") exhibits diversity and contingency (Barrett, 2021). For instance, the argument for the transition from the "Adaptive Tendency Layer" to the "Evaluative Mind Layer" is that some form of internal evaluation and selection mechanism is functionally necessary for effectively satisfying the meta-constraints in complex, conflict-ridden environments. The nervous system is an excellent evolved solution for this function, but it is not the only logically possible form (theoretically, extremely complex biochemical networks or other mechanisms might achieve similar functions). This principle of "multiple realizability," a core tenet of philosophy of mind and functionalism, allows for the same cognitive functions to be realized by different physical substrates (Piccinini, 2020). Thus, the MCRR framework provides a narrative of functional evolutionary plausibility, which is conceptually consistent with the modern understanding of evolution based on "fitness landscapes"—where multiple alternative adaptive peaks and evolutionary paths exist (McLean & McMenamin, 2022).

3. Systematic Positioning vis-à-vis Related Theories

The MCRR framework resides at the confluence of several major theoretical currents and aims to provide an integrative meta-architecture.

Relation to Autopoietic Theory: The MCRR framework fully incorporates autopoietic theory as the rigorous definition for Level I (the Autopoietic Layer) and the starting point of life, forming one of the cornerstones of this framework (Thompson, 2007). Autopoietic theory provides the most stringent operational definition for "what is life." Building upon this, the MCRR framework further elucidates how autopoietic systems serve as solutions for fulfilling more fundamental physical constraints and become a platform for evolving towards higher-level complexities.

Relation to Life History Theory/Behavioral Ecology: The MCRR framework regards life history theory/behavioral ecology as the precise quantification and application of its tripartite constraints within the domain of biological reproduction and survival strategies (Sibly & Brown, 2020). For instance, classic life history trade-offs (e.g., current reproduction vs. future survival) are direct manifestations of conflicts arising among the "resource acquisition," "process optimization," and "system persistence" constraints within specific survival contexts. The MCRR framework, in turn, provides a more fundamental, universal constraint-based dimension and philosophical justification for these specific biological trade-offs.

Relation to Active Inference/Free Energy Principle:

* **Common Ground:** MCRR shares with active inference the fundamental perspective that systems maintain their boundaries and resist disorder (Friston, 2019).

* **Fundamental Divergence:** Active inference posits prediction error minimization (or free energy boundary minimization) as a singular, unified optimization objective. MCRR, conversely, maintains that resource acquisition, process optimization, and system persistence are three logically incommensurable and often practically conflicting basic dimensions. Modern decision neuroscience suggests that choice behavior stems from the independent computation and weighted integration of values associated with distinct attributes (e.g., reward, cost, risk) (Rangel & Clithero, 2023), aligning better with a multi-objective (Pareto) optimization picture. MCRR provides a richer motivational basis inherently characterized by tension and trade-offs.

* **Relationship:** Consequently, the relationship is complementary rather than competitive. MCRR addresses the explanatory question of "why a certain kind of optimization mechanism is needed" (namely, to cope with the inherent conflict among irreducible multiple constraints), while active inference addresses the computational question of "how a powerful optimization algorithm can be implemented" (i.e., via prediction error minimization to achieve the aforementioned multi-objective trade-offs).

4. Implications, Applications, and Validation

4.1. Theoretical Value

The unifying power of the MCRR framework lies in its provision of a consistent explanatory logic extending from physics to society. This attempt at first-principles-based interdisciplinary integration aligns with the research direction advocated by contemporary complex systems science (Mitchell, 2021). The robustness of its foundation stems from rigorous argumentation starting from the hard constraints of a system's existence. Its explanatory power is particularly notable: the tripartite irreducible constraints naturally accommodate the inherent conflicts in behavior and motivation, which resonates strongly with the increasingly emphasized multi-motivation, multi-system decision-making models in psychology and economics (Crockett, 2023). Consequently, it provides a more realistic naturalistic foundation for these disciplines. Its clear architecture also helps clarify the functional essence of different complexity levels.

4.2. Application Prospects

* Cognitive Neuroscience: The MCRR framework can guide the exploration of distinct or interacting neural circuits corresponding to the evaluation of "acquisition value," "effort cost," and "risk/threat." This offers a new paradigm for decision-making research, moving beyond single "reward" or "error" signals towards studying the parallel computation and competitive integration of multi-dimensional value signals (Lockwood & Klein-Flügge, 2023).

* Computational Psychiatry: This framework supports reconceptualizing mental disorders as specific dysfunctions within the multi-constraint value computation system. For instance, addiction could be viewed as a hyperactivity of the "acquisition" system relative to the "optimization" (cost-control) and "persistence" (long-term risk) systems, while anxiety disorders could be seen as an oversensitivity of the "persistence" system. This perspective of multi-system dysfunction is gaining increasing support in the field (Huys et al., 2022).

* Artificial Intelligence: MCRR provides a meta-guidance framework for designing agents with non-reductive intrinsic motivations. It suggests that to handle real-world multi-objective conflicts, AGI systems may need built-in fundamental drives analogous to the three irreducible constraints, rather than a single utility function. This aligns with research directions in reinforcement learning exploring structured intrinsic motivation (Oudeyer & Kaplan, 2023).

* Social Sciences: The framework provides a deep explanatory model for analyzing cultural differences (e.g., individualism vs. collectivism), viewing them as different long-term stable solutions where different sociocultural contexts set default priorities for the three meta-constraints (Henrich, 2020).

4.3. Testable Propositions

The MCRR framework generates a series of empirically testable hypotheses, enabled by the operationalizability of its concepts. For example, employing neural decoding techniques like fMRI and multi-voxel pattern analysis can directly test whether decision-making tasks involve spatially separable neural representations that encode expected reward (acquisition), subjective effort cost (optimization), and risk/uncertainty (persistence), respectively (Hebart & Baker, 2020). Based on principles of developmental plasticity, one can infer that early-life experiences (e.g., resource scarcity, environmental instability) will lead to lasting neuro-behavioral calibrations on the corresponding valuation dimensions. Experimental paradigms from cross-cultural psychology can be used to test whether individuals from different cultural backgrounds exhibit systematic behavioral differences in social dilemma tasks that align with their culture's default weighting of the three constraints (Henrich, 2020).

5. Conclusion

The Multi-level Constraint Recursive Realization (MCRR) framework proposed in this article aims to provide a new integrative perspective for understanding the continuity of complex systems. Starting from the physical premise of dissipative structure persistence, it deduces three irreducible meta-constraints. Building upon this foundation and using the explanatory principle of "recursive realization," it systematically links existing knowledge—such as autopoietic theory, life history trade-off concepts, and multi-objective decision-making models—to outline a coherent analytical perspective spanning physics, life, mind, and society.

The core intention of the MCRR framework is to offer a heuristic perspective: examining the evolution and adaptation of complex systems through the dynamic trade-offs among the three basic constraints. This perspective helps address the shortcomings of single-optimization-target models in explaining behavioral richness and internal conflict. However, its aim is not to replace these specific theories but to provide a broader conceptual background for them. We hope this framework will serve primarily as a heuristic tool and a communication platform, fostering productive dialogue across disciplines centered on core concepts like "constraints," "adaptation," and "hierarchical

realization," thereby inspiring new questions and avenues for future interdisciplinary research into intelligence, behavior, and culture.

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