

# The Complexity Paradox Boundary: When Decomposition Methods Reach Their Limits

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## Executive Summary

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## Research Problem and Theoretical Framework

Decomposition-based methods constitute the foundation of systems engineering, prescribing understanding through analysis of constituents and relationships (INCOSE, 2023). However, when multiple observers apply identical decomposition procedures to the same phenomenon, they produce irreconcilable frameworks based on their conceptual lenses. Weinberg (1975) documented how electrical engineers identify circuits while computer scientists see algorithms, frameworks employing incommensurable categories with no mapping between them. This dissertation introduces the **Complexity Paradox Boundary (CPB) Theory** to identify *when* analytical and holistic perspectives transition from divergent to contradictory, marking *where* decomposition shifts from approximation to misinformation.

The research identifies three paradox categories with increasing severity: (1) Hierarchical paradoxes creating manageable part-whole tensions; (2) Complementarity paradoxes requiring alternation between incompatible properties; and (3) Orthogonal paradoxes representing complete perspective divergence. Four mechanisms drive this divergence: computational irreducibility (Wolfram, 2002), scale separation (Bar-Yam, 1997), circular causation (Richardson, 1991), and information disconnection (Schreiber, 2000).

## Experiment 1: Agent-Based Modeling of Perspective Evolution

The dissertation employs agent-based modeling and simulation (ABMS) to validate theoretical predictions about perspective divergence. Following Axelrod's (1997) cultural model, the implementation uses  $N$  agents with  $F$  features and  $q$  traits, adapting through neighbor interaction. The novelty involves introducing the **Perspective Coherence (PC) metric**:  $PC = \rho(L(t), G(t))$ , measuring correlation between local and global utility functions.

### Experimental Design:

- Agent Configuration: Grid topology with  $N$  agents possessing cultural (modified: perspectives) features
- Interaction Rules: Probabilistic interaction based on cultural (modified: perceptual) similarity
- Local Utility  $L(t)$ : Average similarity to immediate neighbors
- Global Utility  $G(t)$ : System-wide cultural homogeneity measure
- Critical Measurement: PC transitions from positive through zero to negative

**Key Findings:** The model demonstrates that local optimization produces globally contradictory outcomes under specific conditions. When  $PC < 0$ , analytical decomposition contradicts holistic

understanding, quantifying the orthogonal paradox. Phase transition characteristics confirm the boundary as a critical point.

## Experiment 2: AI-Enhanced Perspective Evolution with GPT Agents

The Python implementation represents a methodological innovation using LLM agents to model perspective evolution with realistic persuasion dynamics. This implementation transforms Axelrod's abstract features into concrete perspectives defended through natural language argumentation.

### Enhanced Metrics Suite:

- Shannon Entropy:  $H = -\sum p(x)\log(p(x))$  measuring perspective diversity
- Clustering Coefficients: Local and global network cohesion metrics
- Community Detection: Cultural regions through modularity analysis
- Information Flow: Transfer entropy between hierarchical levels

**Experimental Protocol:** Initialize 100% GPT-3.5-turbo agents with randomized perspectives → Pairwise interactions with probabilistic persuasion → LLM generates contextual arguments → Track PC evolution alongside entropy/clustering → Detect phase transitions through convergent indicators.

## Computational Results and Contributions

Both experiments provide computational evidence for CPB theory. ABM confirms local similarity-seeking produces global polarization, demonstrates PC metric captures perspective divergence, and shows threshold behavior consistent with phase transitions (Kauffman, 1993). LLM enhancement produces realistic evolution trajectories with entropy collapse preceding orthogonality and convergent metrics enabling robust boundary detection.

This research addresses Keating et al.'s (2003) operational gap through three contributions: (1) Paradox typology for severity assessment; (2) Mechanism identification signaling approaching boundaries; (3) Computational tools for investigating resistant phenomena. The framework transforms decomposition from a universally applied to a conditionally appropriate tool.

## Theoretical Significance

CPB theory operationalizes philosophical recognition of perspective plurality (James, 1909; Kuhn, 1962) into an investigable framework. Most significantly, the orthogonal paradox represents not methodological failure but fundamental epistemological limit (Kovacic & Sousa-Poza, 2013). When complexity drives observer-phenomenon relationships across CPB, resulting orthogonality cannot be overcome, different approaches constitute incommensurable realities rather than incomplete views of singular reality.

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