Modularity, not Integration, underlies Universal Computation in Complex Systems

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Extended Abstract

Motivation. The "law of increasing functional information" holds that evolving systems accumulate structural complexity through selection for function [6], but is silent on *how* this complexity is organized: as tightly integrated wholes, or as loosely coupled modules? This distinction has direct implications for evolutionary accessibility and biological modularity. Elementary cellular automata (ECA) provide an ideal testbed: despite being defined by just eight bits per rule, they span the full spectrum from trivial fixed points to universal computation [7, 5], allowing us to precisely ask whether computational power requires functional integration.

Approach and Methodology. We evolved neural networks using NeuroEvolution of Augmenting Topologies (NEAT) [4] via TensorNEAT [1] to learn all 256 ECA rules across 30 independent runs each, yielding 7,680 converged networks. NEAT starts from minimal architectures and complexifies only when necessary, providing an unbiased probe of the minimum sufficient architecture per rule. Each network was characterized using five information-theoretic measures: Structural Information (I_S), Behavioral Information (I_B), Effective Information (I_E [2]), Integration (Φ, inspired by IIT [3]), and Transfer Entropy (T_E).

Results. A robust inverse relationship emerges between structural complexity and integration (Table 1). Class IV rules (including Turing-complete Rule 110) exhibit the highest structural complexity ($I_S = 208 \pm 39$ bits) yet near-zero integration ($\Phi = 0.017$), while Class III XOR-type rules show maximum integration ($\Phi > 0.45$) with minimal structure ($I_S \approx 83$ bits). Algebraically irreducible functions force tightly coupled implementations, whereas universal computation is achieved through loosely coupled, composable subprocesses. Integration is negatively correlated with architectural variance across runs ($r = -0.23$, $p < 0.001$), revealing that modular rules admit many accessible evolutionary paths while integrated rules occupy narrow, constrained regions of solution space. FI features also recover Wolfram's classification with 98.1% macro cohesion.

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Table 1: Aggregate Functional Information by Wolfram class. Values represent mean ± SD.

Class	I_S (bits)	Hidden nodes	Φ	T_E (bits)
I (24 rules)	166 ± 46	4.6 ± 1.3	0.015 ± 0.014	0.065 ± 0.024
II (183 rules)	191 ± 41	5.3 ± 1.2	0.014 ± 0.021	0.080 ± 0.020
III (43 rules)	192 ± 43	5.5 ± 1.1	0.068 ± 0.134	0.079 ± 0.015
IV (6 rules)	208 ± 39	6.2 ± 1.3	0.017 ± 0.038	0.084 ± 0.009

Conclusions and Outlook. Universal computation in ECA arises from modular compositionality, not tight integration. This refines the law of increasing functional information: evolution accumulates not merely more structure, but *modularly organized* structure that remains accessible to further adaptation. Future work includes extending this analysis to larger rule spaces and alternative substrates, and exploring how FI profiles can guide architectural design for tasks with known algebraic or compositional structure.

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