Intelligence at the Edge of Chaos

Emergence of Intelligence from Complex Rule-based Systems

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Abstract & Motivation

- **Key Question:** Can intelligence emerge simply from exposure to data with the right degree of complexity?
- **Approach:** We pretrain modified GPT-2 models on sequences generated by Elementary Cellular Automata (ECAs) and evaluate them on downstream tasks.
- **Insight:** There exists an "edge of chaos" — a sweet spot where the data is structured yet challenging.

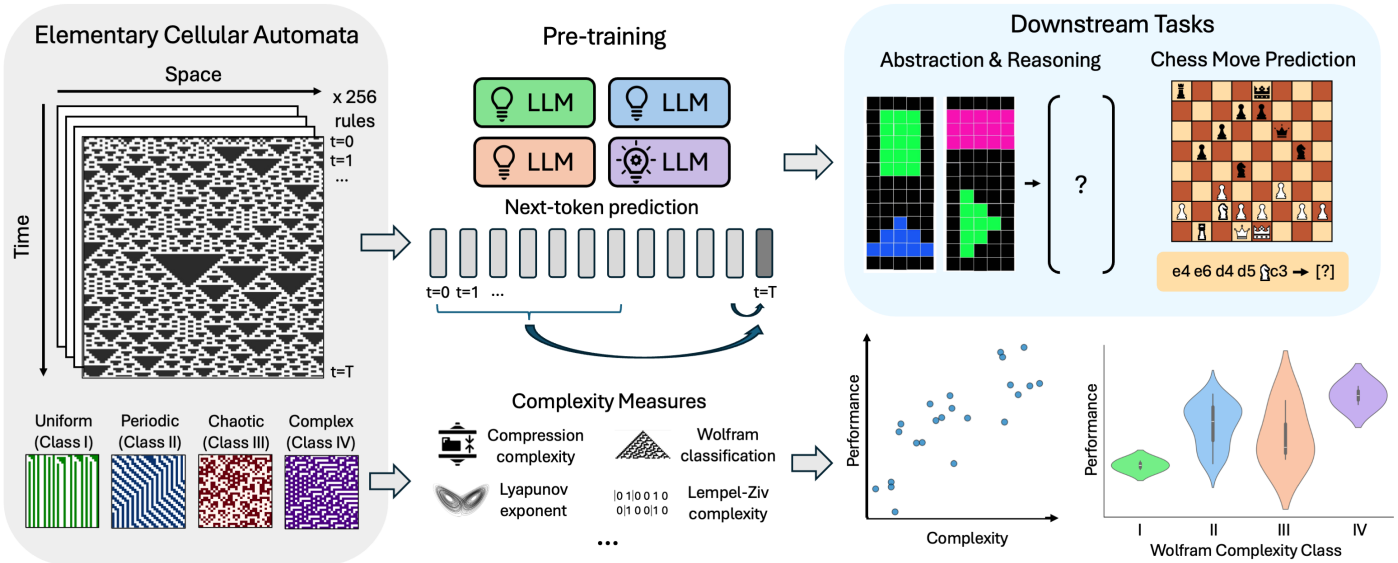


Figure: Framework for investigating the link between complexity and intelligence.

Elementary Cellular Automata & Complexity

- **ECAs:** One-dimensional, binary systems with 256 possible rules.
- **Complexity Classes:**
  - Class I & II: Uniform/periodic (low complexity).
  - Class III & IV: Chaotic/complex (high complexity).
- **Role of Complexity:** Exposure to appropriately complex data may foster emergent intelligent behavior.

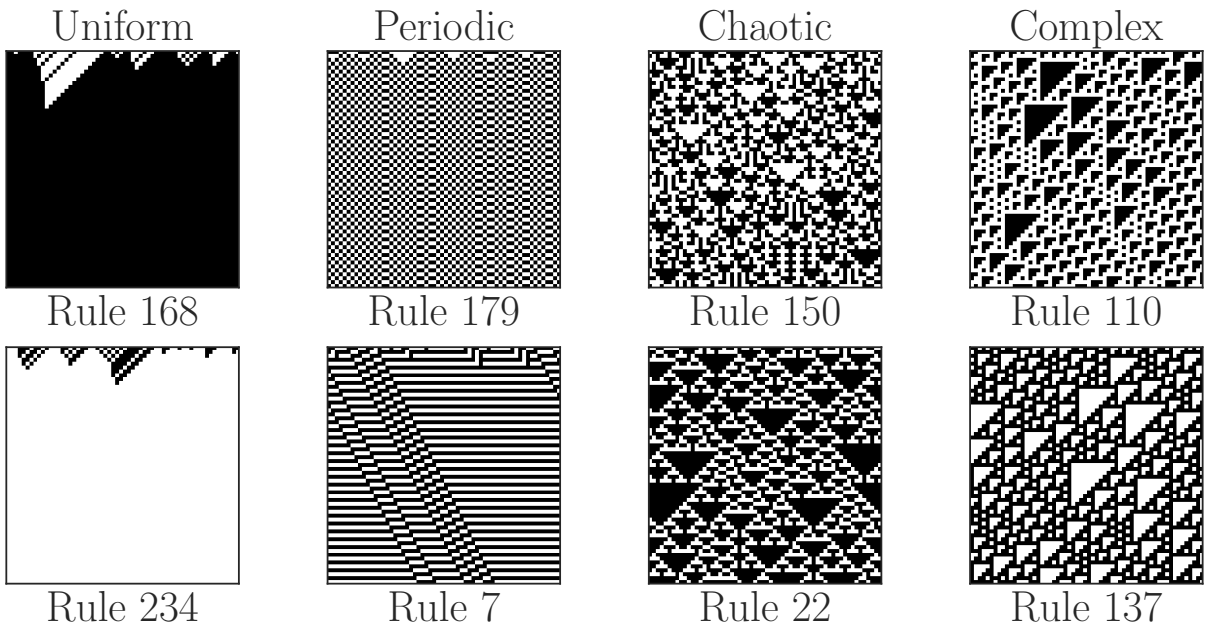


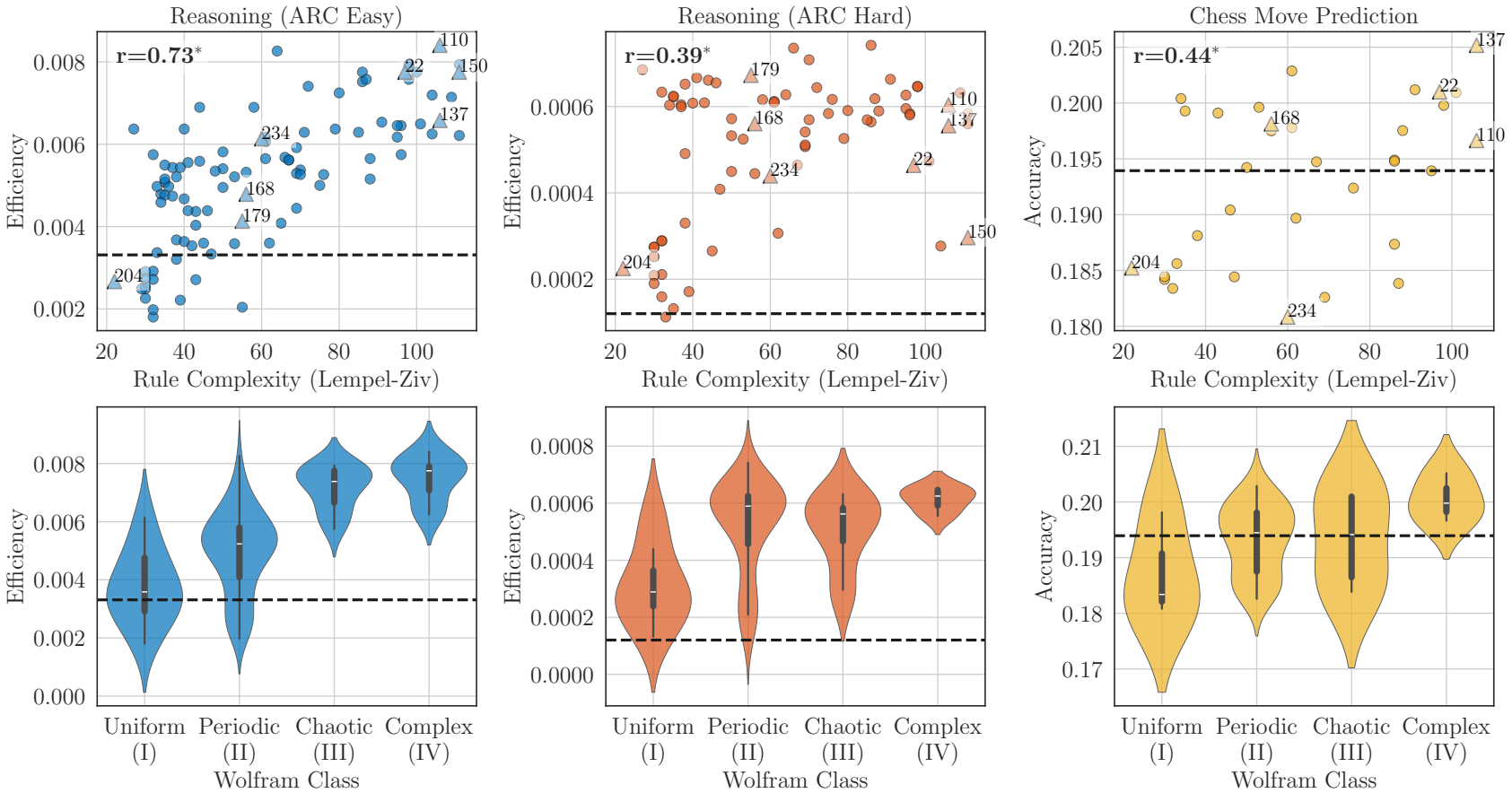
Figure: Example: Wolfram Classification of ECAs and corresponding data complexity.

Data Generation and Pretraining

- **Data Generation:**
  - Simulate ECAs over 1000 time steps.
  - Extract spatiotemporal windows (e.g., 60 steps $\times$ 100 spatial dimensions).
- **Model:** Modified GPT-2 architecture adapted for binary data.
- **Pretraining Setup:**
  - Next-token prediction over up to 10,000 epochs.

Downstream Tasks

- **Reasoning Tasks:** ARC-inspired sequence completion.
- **Chess Move Prediction:** Evaluating strategic reasoning.
- **Nim Game:** Testing optimal move prediction in a classical strategy game.



Key Findings

- **Correlation with Complexity:** Higher ECA data complexity improves downstream performance.
- **Edge of Chaos:** Best performance is observed at an intermediate level of complexity.
- **Attention Analysis:** Models trained on complex data integrate information from longer state histories.

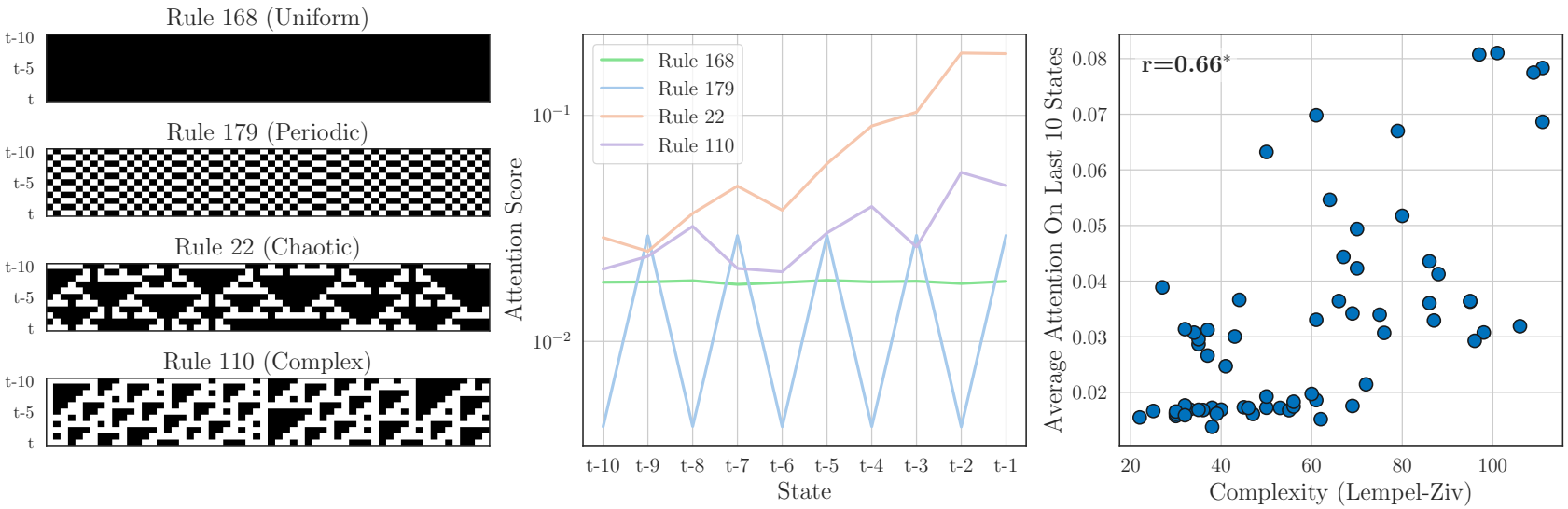


Figure: Relationship between data complexity and model performance (e.g., attention scores).

Discussion and Implications

- The study suggests that intelligence may be an emergent property when systems are exposed to the right balance of order and randomness.
- Our findings highlight the importance of data curation—not just quantity, but intrinsic complexity.
- Future work: scaling experiments, deeper ablations on temporal structure, and extension to other rule-based systems.

Thank You

Questions? Please come visit us at our poster on Thursday, April 24th from 3–5:30pm!

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