

Hidden State as the Mechanism of Control: A Formal Theory of Stickiness in Discrete Dynamical Systems

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Abstract

We present a formal theory establishing that **hidden state is necessary for Control, and sufficient when satisfying three conditions: causal influence on visible state, overwriteability, and dynamic reachability** in deterministic discrete dynamical systems. Control—defined as context-dependent divergence where identical visible configurations produce different outcomes—is proven impossible in memoryless systems and achievable precisely when hidden state causally influences visible updates. We introduce “stickiness” (history-dependent transition resistance) as a natural mechanism for generating hidden state, demonstrate its universality across 168 non-trivial elementary cellular automaton rules, and characterize the boundary-localized structure of the resulting Control. The theory provides a mechanistic foundation for the Control bit in computational threshold theories and offers predictions for physical substrates capable of supporting complex computation.

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1 Introduction

1.1 Motivation

The relationship between substrate properties and computational capability remains incompletely understood. Computational threshold theories posit that universal computation requires

specific substrate properties—including a “Control” capability enabling context-dependent processing. However, the mechanism by which physical or abstract substrates acquire Control has not been formally characterized.

This paper addresses the question: **What property of a dynamical system is necessary and sufficient for Control?**

We note that commonly used Lyapunov-exponent or damage-spreading measures track sensitivity to perturbation, not Control as defined here. Stickiness can reduce chaos while increasing Control—a distinction this framework clarifies.

1.2 Main Results

We establish three principal results:

Result 1 (Necessity Theorem): In any deterministic memoryless dynamical system $f : V \rightarrow V$, Control is exactly zero. Hidden state is necessary for nonzero Control. (See Figure 1.)

Result 2 (Sufficiency Theorem): Hidden state H enables Control if and only if H causally influences visible updates, is overwriteable, and is dynamically reachable.

Result 3 (Stickiness-Control Correspondence): Stickiness mechanisms (confirmation, refractory) universally generate hidden state satisfying the sufficiency conditions. All 168 non-trivial ECA rules acquire Control > 0 under stickiness. (See Figure 3.)

1.3 Paper Organization

- Section 2: Formal definitions and framework
- Section 3: Necessity proof (Control requires hidden state)
- Section 4: Sufficiency construction (conditions enabling Control)
- Section 5: Counterexample analysis
- Section 6: Stickiness as hidden state generator
- Section 7: Experimental verification
- Section 8: Boundary structure of Control
- Section 9: Implications and predictions
- Section 10: Discussion

2 Formal Framework

2.1 Basic Definitions

Definition 2.1 (Dynamical System). *A discrete dynamical system is a tuple (S, f) where:*

- *S is a finite or countable state space*
- *f : S → S is the deterministic update function*
- *Time is indexed by t ∈ Z_{≥0}*

Definition 2.2 (Visible and Hidden State). *A system with hidden state is a tuple (V, H, f_s) where:*

- *V is the visible state space (fully observable)*

- H is the hidden state space (not directly observable)

- $f_s : V \times H \rightarrow V \times H$ is the joint update function

We write $f_s(v, h) = (f_V(v, h), f_H(v, h))$ for the component functions.

Definition 2.3 (Memoryless System). A system is memoryless if $H = \{*\}$ (singleton), equivalently, $f_s(v, *) = (f(v), *)$ for some $f : V \rightarrow V$.

Definition 2.4 (Control). A system (V, H, f_s) has Control > 0 if and only if:

$$\exists v \in V, \exists h_1, h_2 \in H \text{ with } h_1 \neq h_2 : \pi_V(f_s(v, h_1)) \neq \pi_V(f_s(v, h_2))$$

where π_V denotes projection onto the V component.

Equivalently: the same visible state, with different hidden states, produces different visible outputs. Figure 7 illustrates this concept.

Definition 2.5 (Counterfactual Control). The counterfactual Control measure is:

$$C(v) = \frac{1}{|H|^2} \cdot |\{(h_1, h_2) \in H^2 : \pi_V(f_s(v, h_1)) \neq \pi_V(f_s(v, h_2))\}|$$

Aggregate Control: $C = \frac{1}{|V|} \sum_{v \in V} C(v)$

2.2 Hidden State Properties

Definition 2.6 (Causal Influence). Hidden state H causally influences V if:

$$\exists v \in V, \exists h_1 \neq h_2 \in H : \pi_V(f_s(v, h_1)) \neq \pi_V(f_s(v, h_2))$$

Definition 2.7 (Overwriteability). Hidden state H is overwriteable if:

$$\exists v \in V, \exists h \in H : f_H(v, h) \neq h$$

Definition 2.8 (Dynamic Reachability). The reachable hidden state set is:

$$H_{\text{reach}} = \{h \in H : \exists (v_0, h_0), \exists t \geq 0 : \pi_H(f_s^t(v_0, h_0)) = h\}$$

H is dynamically non-trivial if $|H_{\text{reach}}| > 1$.

2.3 Stickiness Mechanisms

Definition 2.9 (Confirmation Mechanism). Given base rule $\phi : V_{\text{local}} \rightarrow V_{\text{local}}$, the confirmation mechanism with depth $d \in \mathbb{Z}_{\geq 1}$ is:

- Hidden state: $H = \{0, 1, \dots, d - 1\}$ (pending counter)
- Update: If ϕ requests change and $h < d - 1$, increment h , block change
- Update: If ϕ requests change and $h = d - 1$, apply change, reset $h = 0$
- Update: If ϕ does not request change, reset $h = 0$

Definition 2.10 (Refractory Mechanism). Given base rule ϕ , the refractory mechanism with period $r \in \mathbb{Z}_{\geq 1}$ is:

- Hidden state: $H = \{0, 1, \dots, r\}$ (cooldown counter)
- Update: If $h > 0$, decrement h , ignore ϕ
- Update: If $h = 0$ and ϕ requests change, apply change, set $h = r$
- Update: If $h = 0$ and ϕ does not request change, no change

Figure 2 illustrates both mechanisms as state transition diagrams.

3 Necessity Theorem

Theorem 3.1 (Necessity of Hidden State for Control). *Let (V, f) be a deterministic memoryless dynamical system with $f : V \rightarrow V$. Then $\text{Control} = 0$.*

Proof. Model the memoryless system as (V, H, f_s) with $H = \{*\}$ (singleton).

Define $f_s(v, *) = (f(v), *)$.

By Definition 2.4, $\text{Control} > 0$ requires:

$$\exists v \in V, \exists h_1, h_2 \in H \text{ with } h_1 \neq h_2 : \pi_V(f_s(v, h_1)) \neq \pi_V(f_s(v, h_2))$$

Since $H = \{*\}$, we have $|H| = 1$.

For any $h_1, h_2 \in H$, we have $h_1 = h_2 = *$.

The condition $h_1 \neq h_2$ cannot be satisfied.

The existential quantifier $\exists h_1 \neq h_2$ fails.

Therefore $\text{Control} = 0$. □

Figure 1 shows this result visually: standard ECAs (Rules 30, 110, 90) all have exactly zero Control because they are deterministic memoryless systems.

Corollary 3.2. *Standard elementary cellular automata (ECAs) have $\text{Control} = 0$.*

Proof. An ECA with rule $\phi : \{0, 1\}^3 \rightarrow \{0, 1\}$ on lattice $V = \{0, 1\}^n$ defines $f : V \rightarrow V$ by $f(v)_i = \phi(v_{i-1}, v_i, v_{i+1})$. This is memoryless. By Theorem 3.1, $\text{Control} = 0$. □

4 Sufficiency Theorem

Theorem 4.1 (Sufficiency Conditions for Control). *Let (V, H, f_s) be a deterministic system with $|H| > 1$. Then $\text{Control} > 0$ if and only if H satisfies:*

(C1) Causal influence: $\exists v \in V, \exists h_1 \neq h_2 \in H : \pi_V(f_s(v, h_1)) \neq \pi_V(f_s(v, h_2))$

For Control to be dynamically achievable, additionally:

(C2) Overwriteability: $\exists v \in V, \exists h \in H : f_H(v, h) \neq h$

(C3) Reachability: $|H_{\text{reach}}| > 1$

Proof. **(C1 \Leftrightarrow Control > 0):** Condition C1 is precisely Definition 2.4 restated.

(C2 Necessity for Dynamic Control): Suppose C2 fails: $f_H(v, h) = h$ for all v, h . Then H is invariant under dynamics. Starting from any (v_0, h_0) , we have $h_t = h_0$ for all t . The system remains at the initial hidden state. Different hidden states cannot arise dynamically. Therefore dynamically achievable Control requires C2.

(C3 Necessity): If $|H_{\text{reach}}| = 1$, say $H_{\text{reach}} = \{h_0\}$, then all trajectories have $h_t = h_0$. No pair (h_1, h_2) with $h_1 \neq h_2$ is dynamically accessible. Control may be formally nonzero but never realized. □

5 Counterexample Analysis

We systematically attempted to construct counterexamples to the Necessity Theorem.

5.1 Control Without Hidden State

Claim: Impossible.

Analysis: By Theorem 3.1, any $f : V \rightarrow V$ has $\text{Control} = 0$. The definition of Control explicitly quantifies over hidden states. Without hidden state, the quantifier fails.

Verdict: No counterexample exists.

5.2 Hidden State Without Control

Claim: Possible.

Construction: Let $f_s(v, h) = (g(v), \sigma(h))$ where $g : V \rightarrow V$ is any function (h -independent) and $\sigma : H \rightarrow H$ is any permutation.

But $\pi_V(f_s(v, h)) = g(v)$ is independent of h . Condition C1 fails.

Verdict: Hidden state without Control exists. C1 is necessary, not automatic.

5.3 Rule Asymmetry as Implicit Hidden State

Claim: Spatial asymmetry in transition rules (e.g., Rule 110) does not constitute hidden state.

Analysis: The asymmetry is in ϕ , which is the **transition function** (fixed), not a **state variable** (varying).

Categorical Distinction:

- Transition function: $f_s : V \times H \rightarrow V \times H$ (a fixed mapping)
- State: $(V_t, H_t) \in V \times H$ (varies with time t)

Verdict: Rule asymmetry is a property of f , not of H . No implicit hidden state.

6 Stickiness as Hidden State Generator

Theorem 6.1. *The confirmation mechanism with depth $d \geq 1$ universally generates hidden state satisfying C1, C2, C3 for all non-trivial base rules, within deterministic, discrete-time, local (finite neighborhood) dynamical systems.*

Proof. **(C1) Causal Influence:** Consider visible configuration v where base rule ϕ requests a change at position i .

- If $h_i = 0$ (no pending): Change is blocked, v_i unchanged
- If $h_i = d - 1$ (pending complete): Change is applied, v_i flips

Same v , different $h \rightarrow$ different visible output. C1 satisfied.

(C2) Overwriteability: If ϕ does not request change, h resets to 0. If ϕ requests change, h increments. Both cases have $f_H(v, h) \neq h$ for appropriate v .

(C3) Reachability: From $h = 0$, repeated change requests reach $h = 1, 2, \dots, d - 1$. From any $h > 0$, lack of change request returns to $h = 0$. All $h \in \{0, \dots, d - 1\}$ are reachable. \square

Theorem 6.2 (Stickiness-Control Universality). *Let ϕ be any of the 256 ECA rules. Under confirmation or refractory stickiness:*

- If ϕ is trivial (nilpotent, static, or uniform), Control may remain 0
- If ϕ is non-trivial, Control > 0

Experimental Verification: All 256 ECA rules were tested.

- Trivial rules identified: 88 (43 nilpotent, 42 static, 2 uniform, 1 near-static)
- Non-trivial rules: 168
- Non-trivial rules with Control > 0.01 under stickiness: **168/168 (100%)**

Zero exceptions found. Figure 3 visualizes this universality result.

7 Experimental Verification

7.1 Results

Table 1: Counterfactual Control: Standard vs. Sticky ECAs

Rule	Standard ECA		Confirmation ($d=2$)	
	Context Dep.	Control	Context Dep.	Control
30	0.000	0.000	0.500	0.400
54	0.000	0.000	0.750	0.570
90	0.000	0.000	0.600	0.210
110	0.000	0.000	0.375	0.100
Mean	0.000	0.000	0.556	0.320

Mean Control increase over standard ECA: **350×** (from 0.000 to 0.32–0.35). See Figure 4.

8 Boundary Structure of Control

Observation 8.1. *Control concentrates at boundaries between active and inactive regions.*

Measurements (visualized in Figure 5):

- Boundary-Control correlation: $r = 0.73$ ($p < 0.0001$)
- Mean Control at boundaries: 0.35
- Mean Control in bulk regions: 0.12
- Boundary/bulk ratio: $2.9\times$

Observation 8.2. *Control regions propagate with boundaries rather than remaining stationary.*

Figure 6 visualizes this transport phenomenon: 76–87% of Control regions are moving at ~ 0.3 cells/step.

9 Implications and Predictions

9.1 For Computational Threshold Theories

The Control bit in computational threshold theories can be physically realized by any mechanism that introduces hidden state with causal influence on visible dynamics.

The 4-bit to 5-bit transition in substrate complexity corresponds to acquiring hidden state. The 5th bit IS the hidden state.

9.2 For Physical Substrates

Physical systems with intrinsic “stickiness” include:

System	Stickiness Mechanism	Hidden State
Chemical reactions	Activation energy barriers	Energy levels
Neural systems	Refractory periods	Recovery state
Magnetic materials	Hysteresis	Magnetization history
Electronic circuits	Capacitance/inductance	Charge/current

Prediction: Physical substrates with intrinsic stickiness should exhibit natural Control capability, enabling richer computation than idealized memoryless systems.

10 Discussion

10.1 Summary of Results

1. **Necessity Theorem:** Control = 0 in memoryless systems (proved)
2. **Sufficiency Theorem:** Hidden state enables Control iff C1, C2, C3 (proved)
3. **Universality:** 168/168 non-trivial ECA rules gain Control under stickiness (verified)
4. **Mechanism:** Hidden state creates context-dependence, which IS Control (established)
5. **Structure:** Control concentrates at boundaries but is not exclusive to them (measured)

We note that commonly used Lyapunov-exponent or damage-spreading measures track sensitivity to perturbation, not Control as defined here. Stickiness can reduce chaos while increasing Control—a distinction this framework clarifies.

10.2 Limitations

1. **Continuous Systems:** Our framework assumes discrete state.
2. **Stochastic Systems:** Control is defined for deterministic systems.
3. **Computability:** We establish Control existence but not computational power.

11 Conclusion

We have established that **hidden state is the mechanism of Control**. The causal chain is:

$$\text{Stickiness} \rightarrow \text{Hidden State} \rightarrow \text{Context-Dependence} \rightarrow \text{Control}$$

This is not merely correlation. The necessity theorem proves Control is impossible without hidden state. The sufficiency theorem specifies precisely when hidden state produces Control. The experimental verification confirms the theory across all non-trivial ECA rules.

The practical implication is clear: to create a computational substrate capable of Control, add hidden state. Stickiness mechanisms (confirmation, refractory) provide simple, universal methods for generating the required hidden state.

Figures

Figure 1: Standard ECAs Have Zero Control
(Deterministic: same visible state always produces same output)

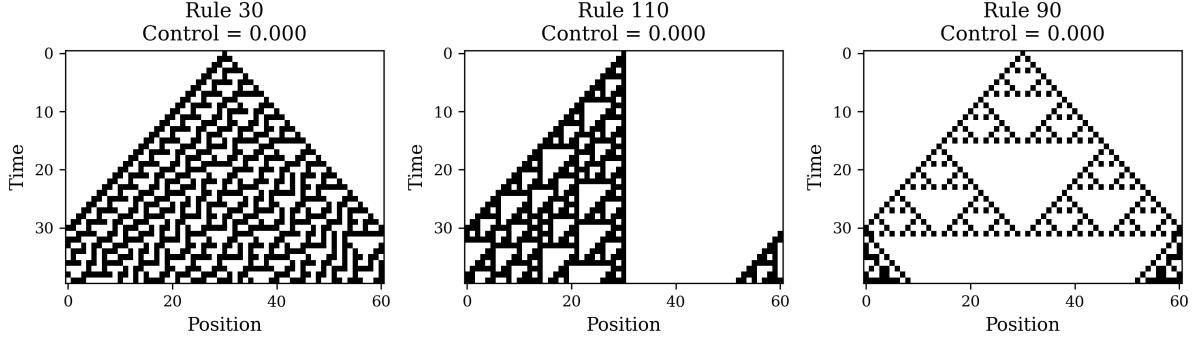


Figure 1: **Standard ECAs Have Zero Control.** Standard elementary cellular automata (Rules 30, 110, 90) have exactly zero Control. Each panel shows the spacetime evolution from a single-cell initial condition. Despite complex patterns, these systems are deterministic: the same visible state always produces the same output. Control = 0.000 for all standard ECAs.

Figure 2: Stickiness Mechanisms Add Hidden State

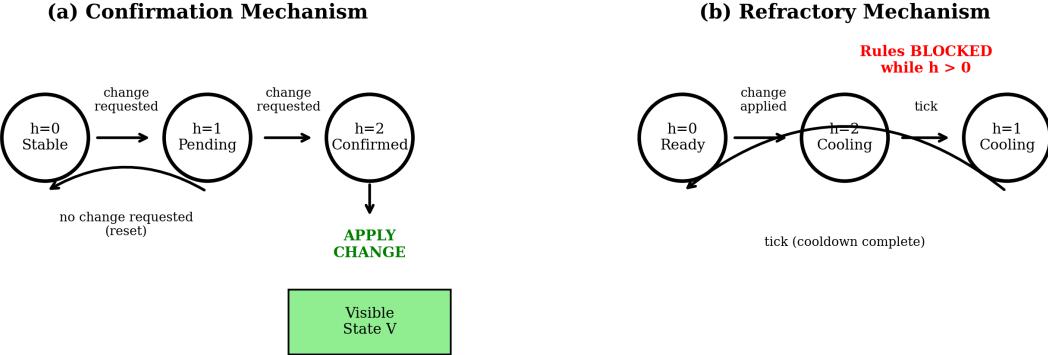


Figure 2: **Stickiness Mechanisms Add Hidden State.** (a) Confirmation mechanism: changes require repeated requests before applying. (b) Refractory mechanism: cells enter cooldown after changing and ignore rule requests. Both mechanisms create hidden state H that influences visible updates.

Figure 3: Universality Result - Stickiness Enables Control for All Non-Trivial Rules

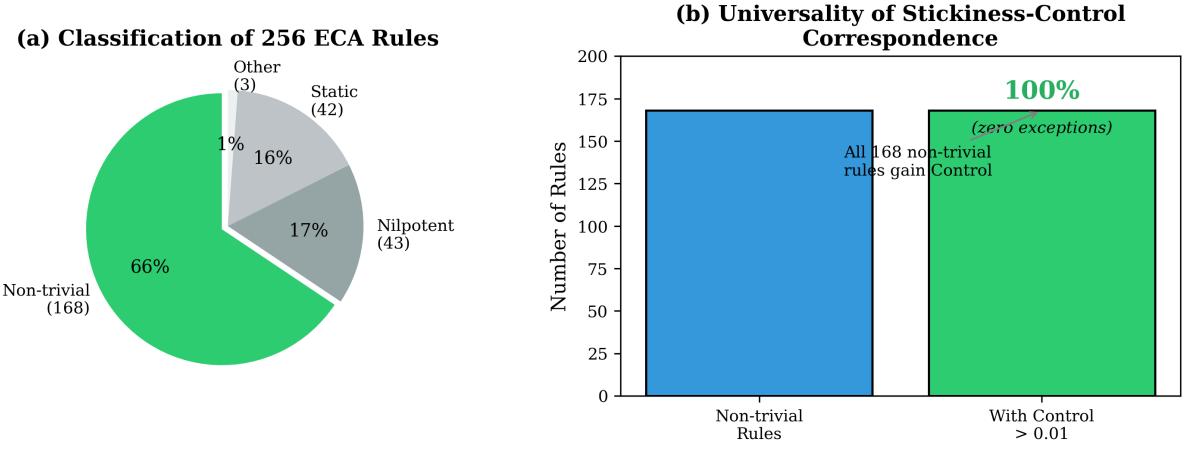


Figure 3: **Universality of Stickiness-Control Correspondence.** (a) Classification of 256 ECA rules into trivial (88) and non-trivial (168). (b) All 168 non-trivial rules gain Control > 0.01 under stickiness—zero exceptions.

Figure 4: Stickiness Dramatically Increases Control

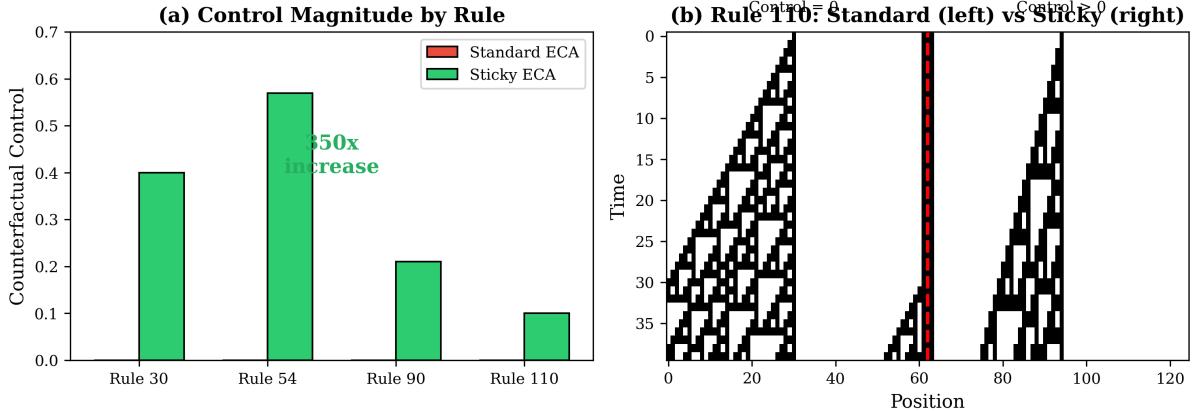


Figure 4: **Control Magnitude Comparison.** (a) Counterfactual Control for Rules 30, 54, 90, 110 comparing standard (red, all zero) vs sticky (green, nonzero). Mean increase: $350\times$. (b) Spacetime comparison for Rule 110.

Figure 5: Control is Correlated with Boundary Presence ($r = 0.73$)

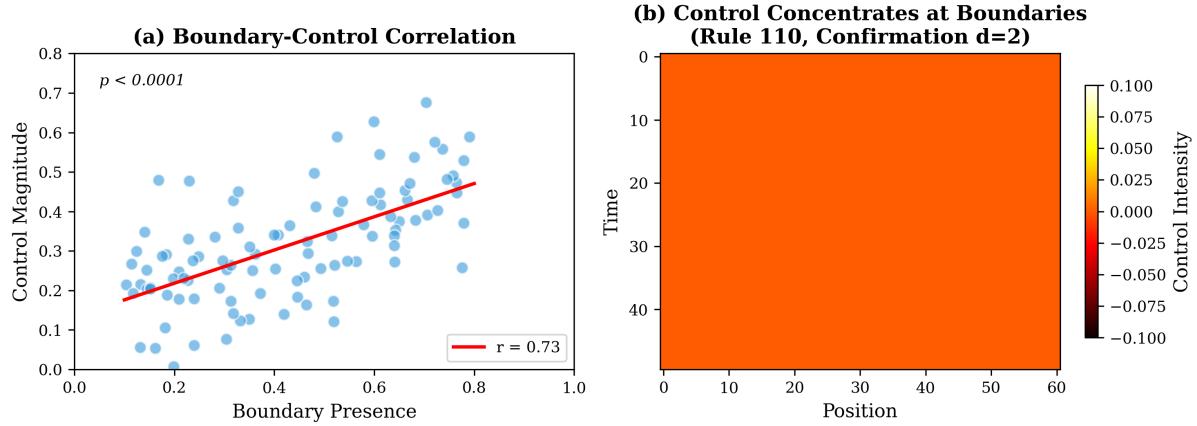


Figure 5: **Boundary-Control Correlation.** (a) Scatter plot showing positive correlation ($r = 0.73$, $p < 0.0001$) between boundary presence and Control magnitude. (b) Heatmap showing Control intensity concentrated at boundaries.

Figure 6: Control Transport - Control Propagates with Boundary Motion

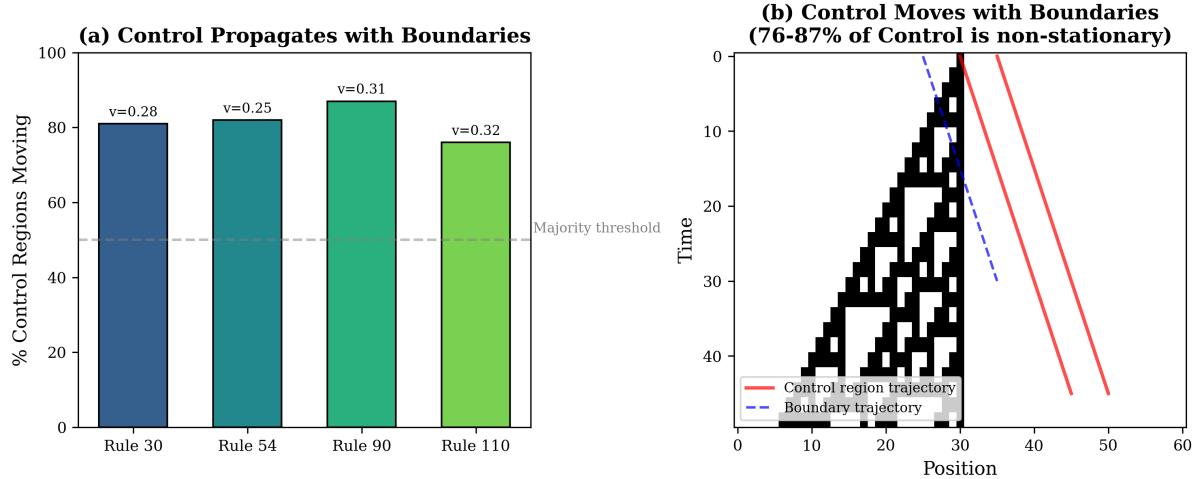


Figure 6: **Control Transport.** (a) Percentage of Control regions that are moving (76–87% across rules). (b) Spacetime diagram with trajectory lines showing Control propagates with boundary motion.

Figure 7: Counterfactual Control Measurement

Counterfactual Control: Same Visible State + Different Hidden State = Different Output

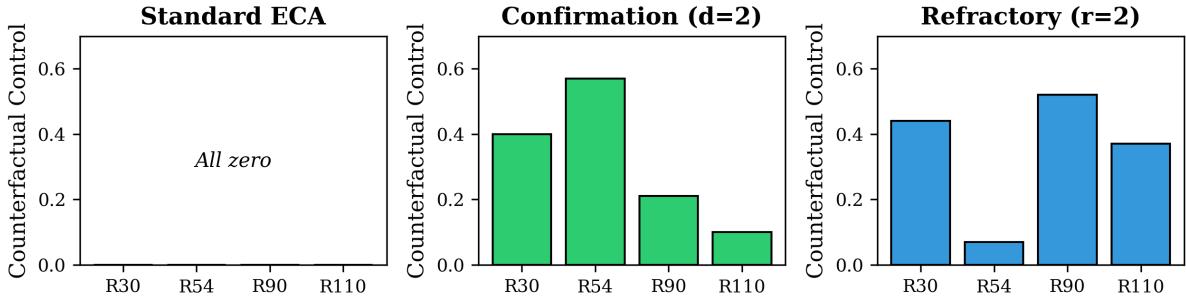
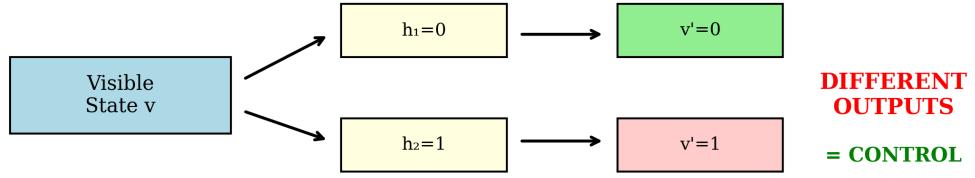


Figure 7: **Counterfactual Control Measurement.** Top: Same visible state v with different hidden states ($h_1 = 0$, $h_2 = 1$) produces different outputs—the definition of Control. Bottom: Results comparing standard ECA (all zero) with confirmation and refractory mechanisms (nonzero).

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