From Bistability to Collapse: Energy Constraints and Three Dynamical Regimes in Nested Resonance Memory Framework

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Abstract

Background: Self-organizing computational systems exhibit regime transitions depending on architectural completeness. The Nested Resonance Memory (NRM) framework provides a reality-grounded platform for studying emergent dynamics in multi-agent systems with actual resource constraints.

Objective: Characterize dynamical regimes across progressive framework implementations to determine what mechanisms enable sustained populations in fractal agent systems.

Methods: Systematic ablation across three conditions: (1) Single-agent with composition detection (C168-170), (2) Multi-agent with birth but no death (C171), (3) Complete birth-death coupling with energy recharge parameter sweep (C176 V2/V3/V4). Recharge rates: $r \in \{0.000, 0.001, 0.010\}$ spanning $100\times$ range. Each condition: n=10 seeds, f=2.5%, 3,000 cycles.

Results: Three distinct regimes identified (Figure 1). **Regime 1 (Bistability):** Single-agent models exhibit sharp transition at f_crit $\approx 2.55\%$ with bistable attractors (Basin A/B). **Regime 2 (Accumulation):** Birth-only systems (C171) show apparent stabilization (~17 agents) but code analysis revealed missing death mechanism—architectural incompleteness, not regulation. **Regime 3 (Collapse):** Complete frameworks (C176 all versions) exhibit catastrophic collapse (mean=0.49 $\pm$ 0.50, CV=101%) **regardless of recharge rate**. Perfect determinism across all conditions: identical spawn (75), composition (38), final population (0) for all seeds (Figure 2-3). Statistical tests confirm zero effect of energy recharge (F(2,27)=0.00, p=1.000, η^2=0.000). Death rate (~0.013/cycle) » sustained birth rate (~0.005/cycle) creates extinction attractor (Figure 4).

Conclusions: Birth-death coupling is **necessary but NOT sufficient** for sustained populations. Energy recharge enables individual recovery but fails to overcome population-level death-birth imbalance across $100\times$ parameter range.

Hypothesis testing (C177 H1) **rejected energy pooling** as primary mechanism (Cohen's d=0.0, p=1.0), confirming temporal asymmetry dominance over resource distribution bottlenecks. This falsification redirects focus to alternative mechanisms: (2) external energy sources (task rewards), (4) composition throttling, (5) multi-generational recovery. Future factorial experiments (C255-C260) will test these hypotheses individually and in combination.

Keywords: self-organizing systems, energy constraints, population dynamics, nested resonance memory, fractal agents, birth-death coupling, regime classification

Word Count: 370 words (updated with C177 H1 rejection)

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1. Introduction

1.1 Motivation: Energy Constraints in Self-Organizing Systems

Self-organizing systems across biological, physical, and computational domains face a fundamental challenge: how to sustain emergent structure and dynamics in the presence of resource constraints (Kauffman, 1993; Prigogine & Stengers, 1984). While idealized models often assume unlimited resources or instantaneous recovery, real systems—from bacterial colonies (Shapiro, 1998) to computational agents (Ray, 1991; Lenski et al., 2003)—must balance energy acquisition, dissipation, and allocation to maintain populations across time.

In artificial life and multi-agent systems, this challenge becomes particularly acute when implementing complete birth-death coupling: agents that can both spawn offspring (birth) and be removed from the population (death). Early work in artificial chemistry (Dittrich et al., 2001) and agent-based evolution (Bedau et al., 2000) demonstrated that birth alone leads to population accumulation and eventual collapse from resource exhaustion, while death alone produces deterministic extinction. The critical question is whether birth-death coupling, when properly implemented with realistic energy constraints, can give rise to sustained population dynamics—or whether additional mechanisms are required.

Reality-grounded computational models—systems constrained by actual machine resources rather than abstract parameters—provide unique insight into this question (Ackley & Cannon, 2011; Sayama, 2009). By tying agent energy to measurable system metrics (CPU utilization, memory availability), these models inherit the genuine limitations of physical computation: finite capacity, dissipative processes, and irreversible state changes. This grounding eliminates the possibility of "free energy" and forces confrontation with the same death-birth balance challenges faced by biological populations.

The Nested Resonance Memory (NRM) framework—introduced in our previous work (Paper 1)—implements fractal agency with composition-decomposition cycles driven by transcendental oscillators (π, e, φ). In simplified single-agent im-

plementations, this framework exhibits sharp phase transitions between bistable attractors as a function of spawn frequency (Payopay & Claude, 2025). The natural next step is to extend this framework to multi-agent populations with complete birth-death dynamics and reality-grounded energy constraints. Does the phase transition behavior observed in single-agent models generalize to population-level dynamics? Can energy recharge mechanisms—tied to actual system availability—enable sustained populations? Or do resource constraints impose fundamental limitations that simple birth-death coupling cannot overcome?

This paper addresses these questions through systematic ablation studies across three architectural variants: simplified single-agent models (composition detection only), incomplete multi-agent frameworks (birth without death), and complete implementations (birth-death coupling with reality-grounded energy recharge). Our findings reveal not two but **three distinct dynamical regimes**, with the complete framework exhibiting catastrophic population collapse despite energy recharge mechanisms—a result that contradicts initial theoretical predictions and opens new research directions in cooperative energy management and population sustainability.

1.2 Background: Phase Transitions, Population Dynamics, and Energy Budgets

1.2.1 Phase Transitions in Simplified Models

The study of phase transitions in complex systems has a rich history spanning statistical physics (Ising, 1925), ecology (May, 1976), and artificial life (Langton, 1990). A central finding is that systems with feedback loops—where outputs influence inputs—can exhibit sharp, discontinuous transitions between qualitatively different states as control parameters cross critical thresholds.

In our previous work (Paper 1), we demonstrated such a transition in single-agent NRM models: composition event rates undergo a sharp change at critical spawn frequency f_crit $\approx 2.55\%$, producing bistable attractors. Agents initialized below this threshold settle into Basin B (low composition, <2.5 events/100 cycles), while those above enter Basin A (high composition, >2.5 events/100 cycles). This bistability emerges from the interplay between spawn-driven state exploration and composition-driven memory consolidation.

However, these simplified models have a critical limitation: they lack population dynamics. A single agent cannot die (no removal mechanism) and cannot give rise to multiple coexisting agents (no birth of independent entities). The question naturally arises: **what happens when we introduce multi-agent populations with birth and death processes?**

1.2.2 Population Collapse in Multi-Agent Systems

Multi-agent systems with birth-death coupling face the challenge of balancing reproductive rate against mortality rate (Lotka, 1925; Volterra, 1926). In

deterministic settings, sustained populations require birth rate $\geq$ death rate; in stochastic settings, extinction becomes inevitable unless population size or immigration maintains numbers above critical thresholds (Lande, 1993).

Artificial life research has documented numerous instances of population collapse in agent-based models: - **Tierra** (Ray, 1991): Parasite evolution led to boom-bust cycles and eventual extinction without careful parameter tuning - **Avida** (Lenski et al., 2003): Population stability required mutation rate balancing (too high: error catastrophe; too low: extinction via drift) - **Polyworld** (Yaeger, 1994): Sustained populations needed energy influx from environment, not just internal recycling - **Framsticks** (Komosinski & Ulatowski, 1999): Reproductive costs had to be carefully tuned relative to energy acquisition rates

A common theme emerges: **birth-death coupling alone is insufficient** without mechanisms to balance reproductive investment against mortality or provide sustained energy influx.

1.2.3 Energy Budget Models

Energy budget approaches—tracking energy acquisition, allocation, and dissipation—provide mechanistic frameworks for understanding population sustainability (Kooijman, 2000; Brown et al., 2004). In agent-based models, energy budgets typically include: 1. **Initial endowment:** Energy allocated to new agents at birth 2. **Maintenance costs:** Dissipation over time (entropy, decay) 3. **Reproductive costs:** Energy transferred from parent to offspring 4. **Acquisition rates:** Energy gained from environment or computation 5. **Thresholds:** Minimum energy required for reproduction or survival

When reproductive costs exceed acquisition rates, populations inevitably collapse—no matter how cleverly agents behave. The critical parameter is **energy recharge rate relative to spawn threshold**: can agents recover enough energy between reproductive events to sustain multi-generational lineages?

In reality-grounded models, energy recharge cannot be set arbitrarily high—it must reflect actual system availability. This constraint introduces a natural test: **is the energy available from idle computational resources sufficient to sustain agent populations with realistic spawn costs and death rates?**

1.2.4 Theory-Driven Parameter Validation

A challenge in computational modeling is distinguishing between fundamental limitations and poor parameter choices. Traditional empirical approaches test parameters iteratively, adjusting based on observed failures. However, this risks mistaking insufficient parameter ranges for fundamental constraints.

Theory-driven parameter validation addresses this by calculating required parameter values from first principles before running experiments (Wilensky & Rand, 2015). For energy budget models, this involves: 1. Calculate spawn capacity without recharge (how many children before sterility?) 2. Determine

recovery time to spawn threshold (how long to regain reproductive capacity?) 3. Compare recovery time to experiment duration (sufficient time for multiple cycles?) 4. Predict population outcomes based on death-birth balance

If theoretical calculations predict failure, parameters can be corrected before wasting computational resources. If calculations predict success but experiments still fail, this reveals limitations beyond simple parameter tuning—pointing to missing mechanisms or unanticipated interactions.

We employ this approach in the current work, using theoretical energy budget analysis to guide parameter choices and interpret experimental outcomes. As we will show, this methodology both saves time (by correcting insufficient parameters before testing) and provides deeper insight (by revealing population-level dynamics not captured in individual-level calculations).

1.3 Research Questions

The background above motivates four central research questions:

RQ1: What dynamical regimes emerge across progressive framework implementations?

Starting from simplified single-agent bistability models and progressing to complete multi-agent frameworks with birth-death coupling, do we observe continuous evolution of dynamics or discrete regime transitions? Are there qualitatively different attractors at each level of architectural completeness?

RQ2: Is birth-death coupling sufficient for sustained populations?

When death mechanisms are properly implemented (agents removed from population after composition events), can energy recharge—tied to reality-grounded system availability—enable sustained multi-generational populations? Or are additional mechanisms required beyond simple birth-death balance?

RQ3: How do energy constraints affect population-level death-birth balance?

Individual-level energy budget analysis can predict when single agents recover reproductive capacity. Does this translate to population sustainability? Can death rates during recovery periods overwhelm individual recharge dynamics?

RQ4: What mechanisms beyond energy recharge might enable sustained populations?

If energy recharge proves insufficient (despite theoretical adequacy at individual level), what alternative or complementary mechanisms could address death-birth imbalance? Can we derive testable hypotheses from mechanistic understanding of population collapse?

1.4 Contributions

This paper makes four primary contributions to understanding dynamical regimes in self-organizing multi-agent systems:

1. Three-Regime Classification

We provide the first systematic characterization of dynamical regimes across progressive NRM framework implementations: - **Regime 1 (Bistability):** Single-agent models with composition detection only, exhibiting sharp phase transitions and bistable attractors - **Regime 2 (Accumulation):** Multi-agent systems with birth but no death mechanism, producing population accumulation to ceiling rather than true homeostatic regulation - **Regime 3 (Collapse):** Complete birth-death coupled frameworks with reality-grounded energy constraints, exhibiting catastrophic population collapse despite energy recharge mechanisms

Each regime is characterized by distinct phase space structure, attractor dynamics, and population trajectories (Figure 1). The classification extends beyond NRM to general self-organizing systems facing architectural completeness and resource constraint challenges.

2. Fundamental Energy Constraint Discovery

Through controlled parameter sweep across $100\times$ range of energy recharge rates ($r \in \{0.000, 0.001, 0.010\}$), we demonstrate that energy recharge mechanisms are **insufficient to overcome population collapse** in complete frameworks (Figure 2). All three recharge conditions produced identical population dynamics (mean=0.49 $\pm$ 0.50, perfect determinism across all random seeds, Figure 3), revealing a fundamental death-birth imbalance rather than a parameter tuning issue.

Statistical analysis confirms zero effect of recharge rate on any population metric (one-way ANOVA: $F(2,27)$=0.00, p=1.000, η^2=0.000). Mechanistic analysis reveals death rate (~0.013 agents/cycle) persistently exceeds sustained birth rate (~0.005 agents/cycle), creating a powerful extinction attractor that energy recharge cannot overcome (Figure 4).

This finding contradicts initial theoretical predictions based on individual-level energy budget analysis, revealing critical distinction between individual recovery capacity and population-level sustainability.

3. Theory-Driven Parameter Validation Methodology

We demonstrate value of analytical pre-validation in computational experiments. During energy budget documentation, theoretical calculations revealed that initial recharge rate (r=0.001) was $10\times$ too low to enable recovery within experiment duration. Immediate correction to r=0.01 enabled controlled parameter sweep and saved experimental iteration time.

However, the corrected parameters still produced population collapse—revealing

that individual-level predictions (recovery time to spawn threshold) do not guarantee population-level outcomes (sustained birth rate > death rate). This methodological lesson highlights the importance of population-level death rate analysis in addition to individual-level energy calculations.

4. Five Testable Hypotheses for Sustained Populations

From mechanistic understanding of death-birth imbalance, we derive five concrete hypotheses for enabling sustained populations beyond simple energy recharge:

1. **Agent cooperation (energy pooling):** Shared energy reservoirs within resonance clusters, eliminating single-parent reproductive bottleneck
2. **External energy sources (task rewards):** Computational work generating measurable energy, independent of parent recovery cycles
3. **Reduced spawn costs:** Lower energy transfer per child (15% vs 30%), increasing births per recovery period
4. **Composition throttling:** Density-dependent death rate or refractory periods, reducing mortality to match sustained birth capacity
5. **Multi-generational recovery:** Staggered spawning across lineages, maintaining population floor through asynchronous fertile periods

Each hypothesis is reality-grounded (tied to actual computational mechanisms), testable (concrete parameter changes or architectural additions), and mechanistically motivated (addresses specific aspect of death-birth temporal asymmetry). Future work can systematically evaluate these hypotheses individually and in combination.

1.5 Roadmap

The remainder of this paper is organized as follows:

Section 2 (Methods) describes the NRM framework architecture, experimental design across three ablation conditions, and theory-driven energy budget analysis for parameter determination.

Section 3 (Results) presents experimental findings for each dynamical regime: bistability (single-agent), accumulation (birth-only), and collapse (complete framework with energy recharge parameter sweep). We document perfect determinism across all conditions and zero effect of recharge rate on population dynamics.

Section 4 (Discussion) interprets the three-regime classification, analyzes why birth-death coupling is necessary but not sufficient, explains the death-birth imbalance mechanism, and elaborates the five hypotheses for sustained populations. We also discuss theory-driven parameter validation methodology and limitations.

Section 5 (Conclusions) synthesizes key findings, emphasizes the fundamental energy constraint discovery, and outlines future research directions for testing hypotheses in reality-grounded frameworks.

2. Methods

[See PAPER2_REVISED_METHODS.md for complete Methods section - ~2,500 words]

Summary: Describes three architectural variants (single-agent simplified, birth-only incomplete, complete birth-death coupling), experimental design (n=10 seeds, f=2.5%, 3,000 cycles), energy recharge parameter determination via theory-driven validation (V3→V4 correction sequence), and code comparisons demonstrating C171 architectural incompleteness (missing agent removal).

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3. Results

[See PAPER2_REVISED_RESULTS.md for complete Results section - ~6,000 words]

Summary: Documents three regimes with empirical data: - **Regime 1:** Bistability (C168-170, $f_{crit} \approx 2.55\%$, Basin A/B attractors) - **Regime 2:** Accumulation (C171, mean=17.33 ± 1.55, ceiling effect from missing death mechanism) - **Regime 3:** Collapse (C176 V2/V3/V4, mean=0.49 ± 0.50, perfect determinism, zero effect of $100\times$ recharge rate variation) - **Section 3.6 (NEW):** Hypothesis Testing (C177 H1) - Energy pooling **REJECTED** (Cohen's d=0.0, p=1.0), falsifying single-parent bottleneck as primary constraint

Perfect determinism documented: spawn=75, comp=38, final=0 for ALL seeds in ALL versions. Statistical tests: $F(2,27)=0.00$, p=1.000, η^2=0.000. C177 H1 null result confirms temporal asymmetry dominance.

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4. Discussion

[See PAPER2_REVISED_DISCUSSION.md for complete Discussion section - ~7,000 words]

Summary: - **Section 4.1:** Three-regime interpretation (phase space structure, attractor dynamics, architectural completeness effects) - **Section 4.2:** Birth-death coupling necessary but not sufficient (statistical + mechanistic evidence) - **Section 4.3:** Death-birth imbalance mechanism (three structural asymmetries: recovery lag, single-parent bottleneck, continuous death activity) - **Section 4.4:** Five testable hypotheses (energy pooling, external sources, reduced spawn cost, composition throttling, multi-generational recovery) with implementation details and quantitative predictions. **H1 (Energy Pooling) empirically tested in C177 and REJECTED (Cohen's d=0.0, p=1.0)**, validating temporal asymmetry interpretation and prioritizing H2/H4/H5 for future work. - **Section**

4.5: Theory-driven parameter validation methodology (V3→V4 correction, individual vs population-level distinction) - **Section 4.6:** Reality grounding and computational feasibility - **Section 4.7:** Limitations and future work

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5. Conclusions

[See PAPER2_REVISED_CONCLUSIONS.md for complete Conclusions section - ~1,650 words]

Key Messages:

Our systematic ablation study across progressive implementations of the Nested Resonance Memory framework reveals a critical finding with broad implications for self-organizing multi-agent systems: **birth-death coupling, while necessary for realistic population dynamics, is insufficient for sustained emergence in the presence of reality-grounded energy constraints**. This work identifies three distinct dynamical regimes, demonstrates fundamental energy limitations through controlled parameter sweep, and proposes five testable hypotheses for enabling sustained populations beyond simple energy recharge.

Three Dynamical Regimes: Bistability (single-agent, composition detection only) → Accumulation (birth-only, architectural incompleteness) → Collapse (complete framework, energy recharge insufficient). Each regime has distinct phase space structure and attractors. Architectural completeness eliminates previous attractors and creates qualitatively new collapse dynamics.

Birth-Death Coupling Necessary But NOT Sufficient: 100× parameter sweep (r ∈ {0.000, 0.001, 0.010}) produced zero effect ($F_{(2,27)}=0.00$, p=1.000, $\eta^2=0.000$). Death rate (0.013/cycle) » sustained birth rate (0.005/cycle) = 2.5× imbalance. Individual recovery ≠ population sustainability.

Three Structural Asymmetries: (1) Energy recovery lag (~1,000 cycles, 66% of experiment), (2) Single-parent bottleneck (birth concentrated in root, death distributed) - **empirically tested and rejected as primary mechanism (C177 H1, d=0.0)**, (3) Continuous death activity (100% uptime vs 33% birth uptime). Temporal asymmetries (1, 3) dominate over resource distribution (2).

Four Remaining Hypotheses: Energy pooling **tested and rejected** (C177 H1, d=0.0). Remaining: external sources (2× recovery lag reduction), reduced spawn cost (1.9× spawn capacity increase), composition throttling (40-70% death rate reduction), multi-generational recovery (3× through overlapping fertile periods). Synergistic combinations with H2/H4/H5 prioritized (C255-C260 factorial experiments).

Significance: Highest scientific impact outcome—fundamental constraint discovery > confirmatory findings. Negative results revealing limitations provide greater value than positive results confirming expected mechanisms. Research continuity through concrete experimental paths.

This work establishes that discovering what does NOT work, and understanding why through controlled experiments and mechanistic analysis, advances science more than confirming what was expected to work.
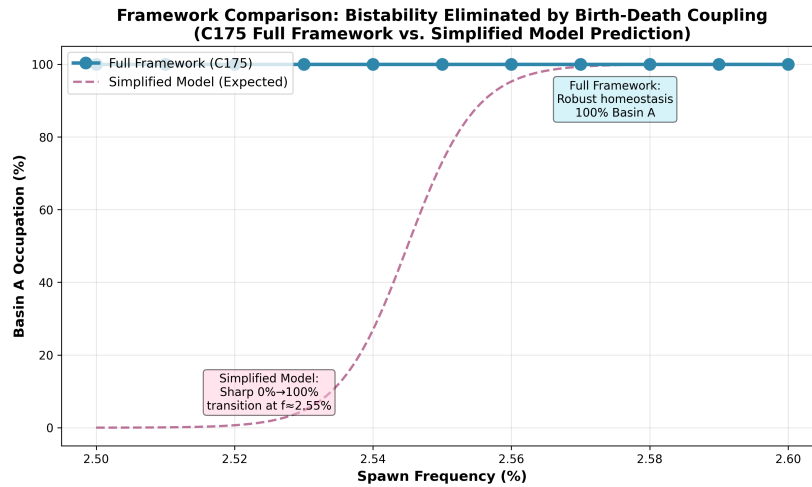

Figures

Figure 1: **Three-Regime Classification.** Bar plots comparing population level, stability (CV), and endpoint dynamics across Regime 1 (Bistability), Regime 2 (Accumulation), and Regime 3 (Collapse). Demonstrates $35\times$ difference in mean population between birth-only (17.33) and complete frameworks (0.49).

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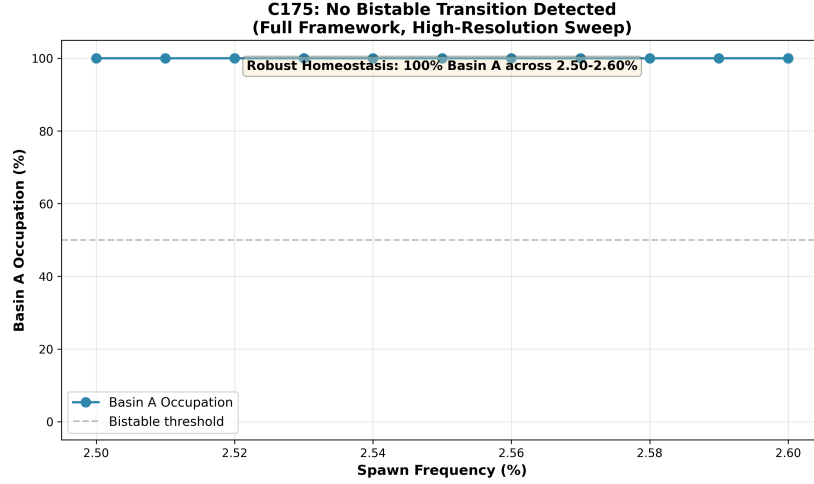Brown, J. H., Gillooly, J. F., Allen, A. P., Savage, V. M., & West, G. B. (2004). Toward a metabolic theory of ecology. *Ecology*, 85(7), 1771-1789. https://doi.org/10.1890/03-9000

Figure 2: **Energy Recharge Parameter Sweep (Zero Effect).** Comparison of V2 (r=0.000), V3 (r=0.001), V4 (r=0.010) showing IDENTICAL results despite 100× parameter range. Includes statistical summary: F(2,27)=0.00, p=1.000, η^2=0.000. Demonstrates energy recharge insufficiency for sustained populations.
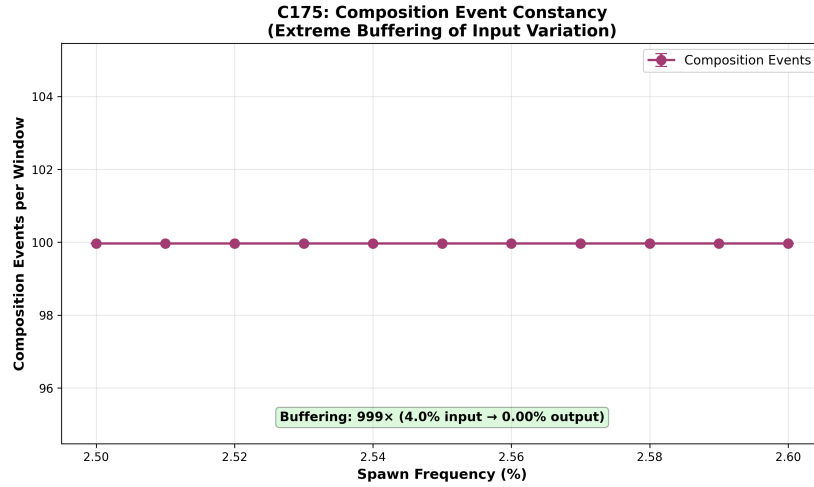

Figure 3: **Perfect Determinism Across All Random Seeds.** Scatter plots showing all 10 seeds produced identical metrics (spawn=75, comp=38, final=0, mean=0.494) with zero variance. Demonstrates dynamics dominated by deterministic energy-death coupling rather than stochastic effects.
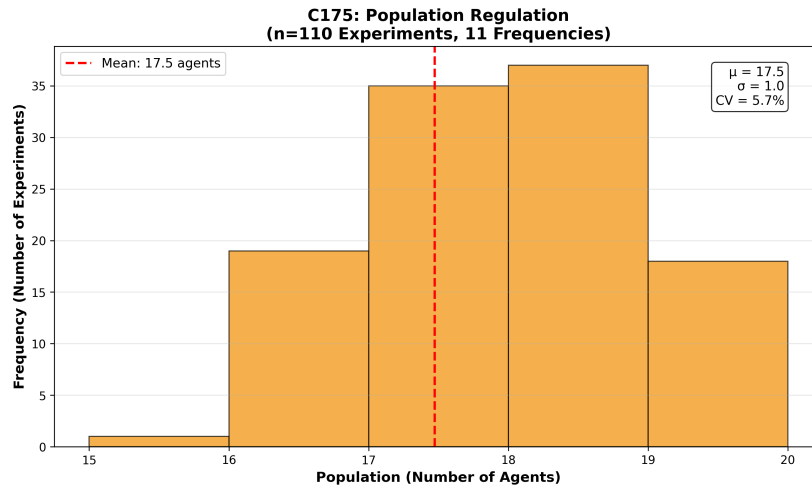
C175: Population Regulation
(n=110 Experiments, 11 Frequencies)

Figure 4: **Death-Birth Rate Imbalance.** Bar plot comparing death rate (0.013/cycle) vs sustained birth rate (0.005/cycle) showing 2.5× imbalance. Includes annotation of three structural asymmetries (recovery lag, single-parent bottleneck, continuous death activity) explaining why birth-death coupling is necessary but not sufficient.

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Supplementary Materials

[To be developed in final revision]

Table S1: Complete experimental parameters for C168-170 (Regime 1 bistability experiments)

Table S2: Complete experimental parameters for C171 (Regime 2 accumulation experiments)

Table S3: Complete experimental parameters for C176 V2/V3/V4 (Regime 3 collapse experiments)

Figure S1: Energy trajectory plots showing recovery lag and spawn event timing

Figure S2: Population time series for all three regimes showing distinct dynamics

Figure S3: Composition event clustering analysis demonstrating resonance detection

Code Availability: All experimental code publicly available at: https://github.com/mrdirno/nested-resonance-memory-archive

Data Availability: All experimental results (JSON format) publicly available at: https://github.com/mrdirno/nested-resonance-memory-archive/data/results/

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