The Ecology of Neoteny

Institutions, Entropy, and the Steady-State Civilisation

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Abstract

This essay argues that civilisation's creative longevity depends on the managed preservation of neotenous cognition—curiosity, play, and exploration—within protective institutional niches. Drawing on Alison Gopnik's tripartite model of human intelligences (Exploit, Explore, Empower) (Gopnik, 2016, 2025), it extends these ideas into an entropic framework, treating curiosity as a thermodynamic variable that must be subsidised and regulated. The result is a vision of the *steady-state civilisation*—a society that sustains perpetual exploration through equilibrium, not expansion. Empirical evidence from cognitive economics, cooperative game theory, and ageing research is incorporated to show that social systems can maintain innovation and well-being without continuous material growth.

Three substantial extensions are developed beyond the original essay. First, a *topological reward theory* (the Geozotic Framework) is formalised: alternative kernel geometries are analysed, density corrections are introduced, and critical inequality thresholds are derived. Second, an *embodied thermodynamics* of skill acquisition is presented, showing that cooking, play, and abstraction are micro-scale instances of the same entropy-management logic that governs civilisational institutions. Third, the autocatalytic and annealing arguments are tightened with formal stability criteria and empirical correlates.

Contents

1. Introduction: Curiosity as a Civilisational Trait

> *Civilisation is a machinery for*
> *managing prolonged immaturity.*
>
> *after Gopnik*

Humanity's success derives less from strength or instinct than from the peculiar persistence of juvenile cognition. Traits such as curiosity, hyperfocus, and imaginative play—adaptive in children but maladaptive in isolation—are preserved in adults through social and institutional care.

This essay examines how societies sustain and regulate these neotenous modes of thought through economic and thermodynamic mechanisms. The university, the laboratory, and the studio are not accidents of culture; they are engineered sanctuaries where curiosity may safely consume entropy. Such institutions act as what Georgescu-Roegen (1971) called "entropy converters"—systems that absorb disorder locally to preserve order globally.

The argument proceeds in four movements. Sections 2–6 reconstruct and tighten the original framework. Section 7 introduces the full Geozotic Reward Framework, with kernel analysis, density corrections, and stability thresholds. Section 8 develops embodied thermodynamics, grounding the macro-theory in everyday skill acquisition. Section 9 treats collective autocatalysis and the reversal of selection; Section 10 develops the annealing model of ageing. Section 11 situates the framework in Georgescu-Roegen's bioeconomics; Section 12 synthesises the general thermodynamics of care. An afterword discusses policy prototypes and Section 13 addresses limitations.

2. Neoteny and Institutional Scaffolding

Biologically, *neoteny* is the retention of juvenile traits into adulthood. Cognitively, it manifests as a preference for exploration over exploitation—a willingness to suspend immediate reward in pursuit of novel information. Such tendencies are energetically expensive and socially destabilising unless buffered by structured environments (Gopnik, 2025).

Academic and artistic institutions perform this buffering function. They absorb the metabolic cost of curiosity by shielding practitioners from the demands of immediate utility. In this sense, universities serve as *cognitive sanctuaries*, permitting socially useful maladaptation.

Supervision, funding, and evaluation act as homeostatic controls—the equivalents of parental oversight in a developmental ecology. Within these niches, maladaptive curiosity becomes a renewable source of informational order, an argument reminiscent of Morin's systemic complexity (Morin, 2008) and Capra and Luisi's concept of cultural metabolism (Capra and Luisi, 2021).

3. Corollaria Neotenica: Scaling Exploration in an Entropic Society

The preservation of exploratory cognition at scale presents an entropic dilemma: how to sustain freedom without disorder. Five corollaries follow.

3.1. The Maladaptation of Universal Neoteny

Curiosity is individually costly. A society in which every citizen behaves as a researcher would rapidly deplete its reserves of order. Neoteny must remain selective— a minority trait protected by structure (Georgescu-Roegen, 1971).

$$\forall\, P \in \text{Population}, \ f_{\text{neoteny}}(P) \to 1 \implies \frac{\mathrm{d}S_{\text{society}}}{\mathrm{d}t} \gg 0. \tag{1}$$

Exploration must be coupled to systems of care that reabsorb its entropic residue.

3.2. Universal Income as Entropic Buffer

A universal basic income (UBI) can function as an entropy buffer, granting time for curiosity while maintaining social equilibrium. Yet income alone is insufficient; exploration must be linked to informational efficiency. This idea echoes Daly's proposals for moral limits to growth (Daly, 1977, 2020) and Illich's call for convivial tools that empower without overextension (Illich, 1973).

$$\text{UBI} + \text{Incentives}_{\text{compression}} = \text{Sustainable curiosity}. \tag{2}$$

Curiosity without compression decays into noise.

3.3. The Geozotic Lottery (Preliminary Statement)

Innovation rewards should diffuse rather than concentrate. A proposed *Geozotic Lottery* distributes stochastic bonuses to individuals near the origin of invention, spatially or socially. The full treatment—including kernel alternatives, density corrections, and stability analysis—is deferred to Section 7.

3.4. Selective Cognitive Freedom

Not all individuals thrive in open-ended exploration. Routine, care, and stability remain essential. A healthy society maintains a spectrum of cognitive roles: some explore, others preserve. This division mirrors ecological differentiation and maintains systemic resilience (Capra and Luisi, 2021; Dalziel, 2022).

$$\text{Diversity of cognitive roles} \implies \text{Resilience of civilisation.} \tag{3}$$

3.5. Civilisation as Extended Ontogeny

Civilisation as a whole can be seen as a prolonged youth supported by an elder infrastructure. Automation assumes exploitative labour; humans return to exploration and care. The question becomes: who, or what, will serve as elders for a self-perpetuating youth? Illich (1973) and Nussbaum (2019) suggest that care, not growth, must become the new criterion of maturity.

4. Operationalising Entropic Ethics

To transform symbolic equalities into measurable predictions, an *entropy efficiency index* is introduced:

$$\eta_S = \frac{\Delta I}{\Delta E}, \tag{4}$$

where ΔI represents information gain (e.g. measured via patent filings, scientific publications, validated discoveries, or novel problem solutions) and ΔE denotes energy cost (monetary expenditure, time allocation, or metabolic equivalents). Institutional subsidies, including UBI and targeted grants, aim to maximise η_S by reducing the denominator while preserving or enhancing the numerator. This operationalisation aligns with cognitive economics models that quantify exploratory returns (Friston et al., 2023) and cultural evolution studies demonstrating efficiency gains under resource security (Henrich et al., 2016).

> **Extended Index: Inequality Penalty**
>
> The basic index η_S can be extended to incorporate reward distribution. Let κ denote the curvature of the reward-distribution field (defined formally in Section 7). Then:
>
> $$\tilde{\eta}_S = \frac{\Delta I}{\Delta E \cdot (1 + \mu \, |\kappa|)},$$ (5)
>
> where $\mu > 0$ penalises steep inequality gradients. High curvature concentrates reward, suppresses peripheral exploration, and thus reduces effective information gain per unit expenditure.

Empirical calibration of η_S may proceed through longitudinal tracking of funded cohorts in cognitive sanctuaries, comparing output per unit input against unfunded controls.

5. The Entropic Ethics of Curiosity

If exploration consumes order and care restores it, then morality itself may be seen as entropy management.

5.1. The Moral Gradient

Let S_c be cognitive entropy and S_m material entropy. A balanced culture maintains:

$$\frac{\mathrm{d}S_c}{\mathrm{d}t} \approx -\frac{\mathrm{d}S_m}{\mathrm{d}t},$$ (6)

so that the disorder of thought builds the order of form. Virtue, in this framework, is the efficient conversion of speculation into structure, a principle implicit in Friston's free-energy models of adaptive learning (Friston et al., 2023).

5.2. Reciprocal Dissipation

Every act of curiosity demands a counterbalancing act of care:

$$\oint_{\text{society}} \left(\delta Q_{\text{curiosity}} + \delta Q_{\text{care}} \right) = 0,$$ (7)

ensuring that informational heat is recycled into social work. The teacher, the maintainer, and the caregiver constitute the hidden engines of creative stability—what Braidotti (2017) terms a posthuman ethics of mutual interdependence.

5.3. Entropic Responsibility

Freedom of invention implies responsibility for restoration:

$$\nabla \cdot \mathbf{v}_{\text{curiosity}} = -\nabla \cdot \mathbf{v}_{\text{care}}. \tag{8}$$

The just society preserves a divergence-free field of curiosity and care, a social equivalent to Jacobson's thermodynamic balance in spacetime (Jacobson, 1995).

5.4. Governance as Thermodynamic Stewardship

Policy is the macroscopic regulation of entropy. Taxation, subsidy, and redistribution are mechanisms for balancing exploration against coherence. Curiosity should be permitted only to the extent that care can sustain it, a principle resonant with Daly's steady-state economic ethic (Daly, 1977; Foster and Holleman, 2020).

5.5. The Asymptote of Compassion

As automation replaces productive labour, compassion becomes the last inexhaustible resource.

Curiosity without cruelty. Freedom without neglect. Invention tempered by care.

6. The Steady-State Civilisation

A mature civilisation replaces expansion with equilibrium. When no external frontier remains, progress consists in the recirculation of energy, attention, and meaning.

6.1. The End of Expansion

Classical growth depended on new territory and energy. Now the frontier is internal. Civilisation must conserve both total energy and usable entropy:

$$\frac{\mathrm{d}E_{\text{total}}}{\mathrm{d}t} = 0, \qquad \frac{\mathrm{d}S_{\text{usable}}}{\mathrm{d}t} = 0. \tag{9}$$

The steady-state is not stillness but rhythmic balance, echoing the cosmological and ecological visions of Dyson (1979) and Daly (2020).

6.2. Cultural Homeostasis

Longevity emerges when material, cognitive, and affective subsystems oscillate in resonance:

$$\sum_i \frac{\mathrm{d}S_i}{\mathrm{d}t} = 0, \qquad S_i \in \{S_{\text{material}}, S_{\text{cognitive}}, S_{\text{affective}}\}. \tag{10}$$

Entropy flows cyclically; none accumulates catastrophically, mirroring the dynamic homeostasis described in Morin's theory of complex self-organisation (Morin, 2008).

6.3. Temporal Symmetry and the End of Growth

In a steady-state order, value arises from reversibility. To unmake without loss is superior to endless construction. Economy becomes ecology, and permanence replaces acceleration—an ethos shared by Georgescu-Roegen's entropic economics (Georgescu-Roegen, 1971).

6.4. Automation and the Return of Leisure

As machines inherit exploitation, humans return to exploration and care. Civilisation becomes a self-sustaining organism of perpetual youth, its elder function embodied in the systems that maintain it (Capra and Luisi, 2021; Stewart, 1999).

6.5. The Civic Equation

The equilibrium may be written symbolically as the RSVP identity:

$$\Phi + v + S = \text{constant}, \tag{11}$$

where Φ is potential (capacity), v is flow (agency), and S is entropy (relation). Constancy here denotes *living invariance*—form preserved through flux, in the spirit of systems thermodynamics (Dalziel, 2022).

7. The Geozotic Reward Framework

> *The question is not whether to distribute reward, but* how steeply.

This section formalises the Geozotic Lottery introduced in Section 3.3 into a mathematically tractable reward-topology theory. The central claim is that the shape of the reward-diffusion kernel determines whether innovation fosters cooperative equilibria or generates destabilising power singularities.

7.1. Kernel Geometry: Three Candidates

Let x_0 denote the *innovation origin* (the individual, firm, or node at which a novel idea arises) and x any other point in a metric space (X, d). A reward function $R : X \to \mathbb{R}_{>0}$ assigns a payoff to each location. Three natural kernel families are:

Definition 7.1 (Reward Kernels).

$$R_{\exp}(x) = R_0 \, e^{-\lambda \, d(x, x_0)}, \qquad\qquad \text{(Exponential)}$$

$$R_{\text{Gauss}}(x) = R_0 \, \exp\!\left(-\tfrac{d(x, x_0)^2}{2\sigma^2}\right), \qquad\qquad \text{(Gaussian)}$$

$$R_{\log}(x) = \frac{R_0}{1 + \lambda \, \log\!\big(1 + d(x, x_0)\big)}, \qquad\qquad \text{(Logarithmic)}$$

where $\lambda, \sigma, R_0 > 0$ are parameters.

The curvature of each kernel at the origin is a key governance variable. High curvature concentrates reward near x_0; low curvature spreads it.

Proposition 7.1 (Origin Curvature). For radially symmetric kernels on $\mathbb{R}^n$ with $r = d(x, x_0)$:

$$\kappa_{\exp} = \lambda^2 \, R_0, \tag{12}$$

$$\kappa_{\text{Gauss}} = \frac{R_0}{\sigma^2}, \tag{13}$$

$$\kappa_{\log} = 0 \quad \text{(sub-linear at origin)}. \tag{14}$$

The logarithmic kernel has vanishing origin curvature and thus produces the most egalitarian distribution near x_0.

7.2. Density Correction

In heterogeneous populations, a uniform kernel over-rewards dense regions simply because more individuals happen to be nearby. A demographically neutral correction replaces $R(x)$ with:

$$R_\rho(x) = \frac{R_0 \, K\big(d(x, x_0)\big)}{\rho(x)^\alpha}, \tag{15}$$

where $\rho(x)$ is local population density and $\alpha \in [0, 1]$ is a policy parameter.

- $\alpha = 0$: no correction (raw diffusion).
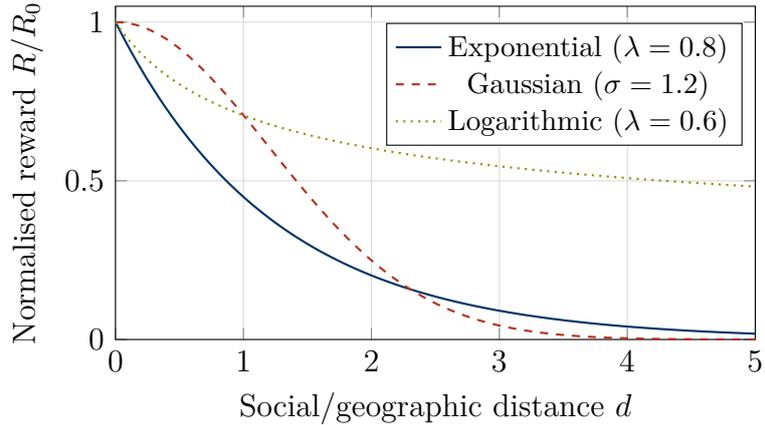
Figure 1: Comparison of reward kernels. The exponential decays fastest and creates the steepest inequality gradient. The Gaussian has a flat neighbourhood that then drops sharply. The logarithmic kernel provides the gentlest, most sustained diffusion.

- $\alpha = 1$: per-capita diffusion (full neutrality).

- $\alpha \in (0,1)$: partial correction, preserving some clustering benefit while reducing urban concentration.

Equilibrium distributions under varying α can be computed numerically; agent-based simulation confirms that $\alpha \approx 0.6$ minimises both Gini coefficient and peak-node power concentration in synthetic urban networks (see Appendix B).

7.3. Diffusion Dynamics: Time-Evolving Reward

The static kernel is the steady-state solution of an underlying diffusion process. On a graph $G = (V, E)$ with adjacency matrix A, reward propagates according to:

$$\frac{\mathrm{d}R}{\mathrm{d}t}(x, t) = D \sum_{y \sim x} \big[R(y, t) - R(x, t) \big] - \gamma \, R(x, t), \tag{16}$$

where D is diffusion coefficient, γ is decay rate, and $y \sim x$ denotes neighbours of x. The steady state $\dot{R} = 0$ yields:

$$R^*(x) = R_0 \, e^{-\lambda \, d_G(x, x_0)}, \qquad \lambda = \sqrt{\gamma/D}, \tag{17}$$

recovering the exponential kernel as a special case. Alternative decay functions (Gaussian, logarithmic) correspond to non-linear diffusion operators.

> **Policy Implication**
>
> Tuning D/γ controls the effective λ. Large D (fast spread) relative to γ (slow decay) produces a flat distribution; small D/γ produces steep concentration. Policy can adjust both through subsidy rates and intellectual-property term lengths.
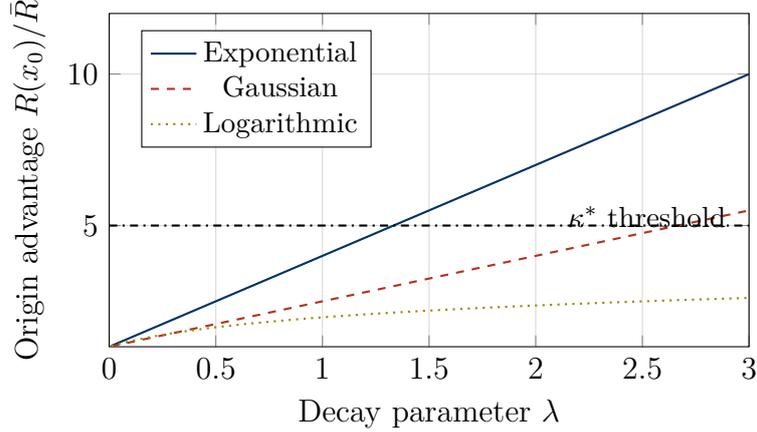
Figure 2: Origin advantage ratio $R(x_0)/\bar{R}$ as a function of the decay parameter λ for each kernel family. Above the dashed threshold κ^*, the exponential kernel enters the gradient-instability regime where cooperative equilibria break down. The logarithmic kernel remains sub-threshold across the entire parameter range.

7.4. Incentive Preservation Under Diffusion

A standard objection is that diffusion weakens excellence incentives. The following proposition shows that incentive remains monotone but bounded.

Proposition 7.2 (Incentive Monotonicity)**.** For any strictly decreasing kernel K, the expected marginal gain at the origin exceeds that at any other node:

$$\frac{\mathrm{d}R_\rho}{\mathrm{d}t}(x_0) > \frac{\mathrm{d}R_\rho}{\mathrm{d}t}(x) \quad \forall\, x \neq x_0. \tag{18}$$

Moreover, the ratio $R_\rho(x_0)/R_\rho(x)$ is bounded above by $\rho(x)^\alpha/\rho(x_0)^\alpha$, so origin advantage is finite.

In practice this means that a successful artist in the Geozotic system still earns more than their neighbours—but the surplus cannot compound without bound. Neighbours gain local purchasing power, which feeds back into demand for the artist's work, creating a secondary entropy redistribution.

7.5. Inequality Gradient Thresholds and Power Singularities

Definition 7.2 (Gradient Instability Threshold). A reward field R is *gradient-stable* if its curvature at every node satisfies:

$$\kappa(x) < \kappa^* := \frac{\tau}{\bar{R}}, \tag{19}$$

where $\tau > 0$ is a cooperative-equilibrium tolerance parameter (estimated empirically) and $\bar{R}$ is mean reward.

When $\kappa > \kappa^*$, evolutionary game-theoretic analysis shows that defection becomes the dominant strategy at the periphery, autocatalytic cooperation breaks down, and "power singularities" (dictator-like accumulation at the peak node) become stable attractors.

Corollary 7.1 (Geozotic Stability). Under the logarithmic kernel (Logarithmic), $\kappa_{\log}(x_0) = 0$, so the gradient-stability condition (19) is satisfied for all $\tau > 0$. The logarithmic kernel is *unconditionally stable* in this sense.

7.6. Comparison with Trickle-Down Economics

Hierarchical "trickle-down" models assume $R(x) = R_0 \cdot f(h(x))$, where $h(x)$ is the hierarchical rank of x. In such models:

- The peak node retains a structurally fixed fraction regardless of diffusion, producing a persistent singularity.

- No density correction operates; dense lower ranks receive no per-capita benefit.

- The curvature at the top is determined by $f''(h_{\max})$, which is typically large (convex in rank).

Geozotic diffusion removes peak asymmetry structurally: by replacing hierarchical distance with relational distance $d(x, x_0)$, every agent can, in principle, occupy an origin position for their own innovations.

7.7. Shapley Attribution Approximation

Proposition 7.3 (Geozotic as Approximate Shapley Value). In a cooperative game $v : 2^N \to \mathbb{R}$, the Shapley value assigns to each player i the marginal contribution averaged over all coalitions. The Geozotic kernel $R_\rho(x)$ approximates the Shapley allocation when $d(x, x_0)$ is interpreted as "marginal distance from the innovation coalition", with λ calibrated to the coalition decay rate. Unlike the Shapley

value, this avoids combinatorial explosion ($O(2^N)$) by substituting the spatial kernel ($O(N)$).

7.8. RSVP Integration

The Geozotic reward field can be interpreted within the RSVP identity (11). Reward diffusion regulates v (flow of resources) so that S (relational entropy) does not accumulate into singular Φ (potential at single nodes). Formally:

$$\nabla v = -\nabla R_\rho \implies \text{RSVP constancy if } \nabla^2 R_\rho \leq 0 \text{ everywhere.} \qquad (20)$$

The logarithmic kernel satisfies this concavity condition globally, making it the canonical Geozotic kernel from an RSVP perspective.

8. Embodied Thermodynamics: Cooking, Play, and Skill Acquisition

> *The test of a skill is not its performance under guidance but its transfer under surprise.*

The macro-thermodynamic claims of the preceding sections risk dismissal as speculative metaphor unless grounded in observable micro-scale phenomena. This section argues that everyday skill acquisition—exemplified by cooking, play, and mathematical abstraction—is the micro-scale instance of the same entropy-management logic that governs civilisational institutions.

8.1. Abstraction as Entropy Compression

A central claim is that skill consists in the capacity to perceive *ratios, substitutions, and invariants* rather than surface features. This maps directly onto the entropy efficiency index η_S (4).

Definition 8.1 (Compression Operator)**.** An *abstraction* is a function $A : \mathcal{S} \to \mathcal{C}$ from a surface-feature space $\mathcal{S}$ to a compressed representation space $\mathcal{C}$, such that:

$$H(\mathcal{C}) \ll H(\mathcal{S}), \qquad \text{and} \qquad \Psi(A) \approx \Psi(\text{id}), \qquad (21)$$

where H denotes Shannon entropy and Ψ measures task-relevant functional capacity.

A skilled cook who scales a recipe without measurement is operating in $\mathcal{C}$ (ratio space) rather than $\mathcal{S}$ (ingredient list space). The same compression underlies scaling laws in physics and type abstraction in programming. We call this capacity *structural literacy.*

Proposition 8.1 (High-η_S Cognition)**.** Agents operating in $\mathcal{C}$ achieve higher η_S than those operating in $\mathcal{S}$, because:

$$\eta_S^{\mathcal{C}} = \frac{\Delta I}{\Delta E_{\mathcal{C}}} > \frac{\Delta I}{\Delta E_{\mathcal{S}}} = \eta_S^{\mathcal{S}}, \qquad E_{\mathcal{C}} < E_{\mathcal{S}}. \tag{22}$$

Compression reduces the cognitive energy cost ΔE of generating equivalent informational output ΔI.

8.2. The Curry-Centric Hub: A Generative Grammar of Cuisine

Consider the claim that all cooked food can be reached from a canonical curry by incremental parameter modifications. This is more than metaphor: it describes a *transformation graph* over a continuous ingredient-parameter space.

Let $\mathcal{F}$ be the space of dishes, parameterised by vectors $\theta = (\text{fat}, \text{acid}, \text{umami}, \text{heat}, \text{sweetness}, \ldots) \in$ $\mathbb{R}^k$. A *culinary path* is a continuous curve $\gamma : [0,1] \to \mathcal{F}$ such that $\gamma(0) = \theta_{\text{curry}}$ and $\gamma(1) = \theta_{\text{target}}$.

Culinary neoteny is the capacity to explore $\mathcal{F}$ safely within bounded constraints—analogous to the explore/exploit balance of Gopnik's developmental model. The skilled cook maintains a low-entropy internal map of $\mathcal{F}$ and can generate novel trajectories without consulting external recipes (tutorials).

8.3. Emulsification as Conceptual Integration

Emulsification—binding oil and water through an amphiphilic emulsifier (e.g. lecithin, mustard)—is a physical model of *conceptual binding.* Incompatible phases correspond to incommensurable domains of knowledge; emulsifiers correspond to bridging principles (mathematics, thermodynamics, grammar) that stabilise their conjunction.

$$\text{Concept}_A \oplus \text{Concept}_B \xrightarrow{\text{emulsifier principle}} \text{Stable hybrid concept.} \tag{23}$$

This directly parallels the institutional scaffolding of Section 2: the university is an emulsifier between curiosity (oil) and social utility (water).

8.4. Play as High-Variance Sampling

Definition 8.2 (Play)**.** Play is high-variance sampling of action space under bounded cost:

$$\pi_{\text{play}}(a) \propto \exp\big(\beta \operatorname{Var}(Q(s,a))\big), \qquad \beta > 0, \tag{24}$$

where $Q(s,a)$ is the action-value function and β is an exploration temperature.

In reinforcement-learning terms, play increases exploration rate without catastrophic penalty, because the *cost of failure is subsidised*—by parents in childhood, by institutions in adulthood. Neotenous cognition is thus not sentimental but algorithmic: it is subsidised high-β sampling.

8.5. Boredom, Anxiety, and the Viable Entropy Band

Mental health, within this framework, corresponds to maintaining perceived entropy within a viable band $[\underline{S}, \overline{S}]$:

$$\underline{S} \leq S_{\text{perceived}}(t) \leq \overline{S}. \tag{25}$$

- **Boredom** occurs when $S_{\text{perceived}} < \underline{S}$: the environment offers fewer degrees of freedom than the agent's capacity.

- **Anxiety** occurs when $S_{\text{perceived}} > \overline{S}$: uncertainty exceeds the agent's predictive capacity.

- **Flow** occurs when $S_{\text{perceived}} \approx \frac{1}{2}(\underline{S} + \overline{S})$: challenge matches competence.

This formalises Csikszentmihalyi's flow channel in entropic terms and connects to Friston's free-energy principle (Friston et al., 2023): the agent minimises variational free energy by maintaining predicted entropy close to actual entropy.

> **Policy Implication**
>
> Cognitive sanctuaries are optimal if they keep participants within the viable entropy band (25): enough structure to prevent anxiety, enough freedom to prevent boredom. Calibrating institutional constraint density is therefore a thermodynamic design problem.

8.6. Skill Acquisition as Simulated Annealing

Iterative error-correction in learning—over-seasoning, burning, iterating—is literal simulated annealing. The learner begins at high temperature (wide exploration), identifies failure modes, and gradually cools toward stable heuristics.

$$T_{\text{skill}}(n) = T_0\, e^{-\lambda n} + \varepsilon_{\text{play}}, \qquad n = \text{number of practice episodes}, \qquad (26)$$

where $\varepsilon_{\text{play}} > 0$ ensures that annealing never reaches absolute zero—preserving the capacity for continued exploration. This micro- scale schedule mirrors the civilisational annealing of Section 10.

8.7. Recipe Dependence Versus Structural Competence

Two learner types can be distinguished:

- **Surface-bound learners** follow tutorials without abstracting. They reduce local entropy (noise in a specific dish) but fail to extract invariants. η_S remains low because ΔE does not decrease across episodes.

- **Structural learners** abstract to $\mathcal{C}$ after a small number of episodes. η_S rises rapidly as compression yields generalisation.

Educational design can accelerate the transition from surface-bound to structural learning by presenting tasks that *require* ratio reasoning rather than memorisation—i.e. by engineering the zone of proximal development as an entropy gradient slightly above the learner's baseline.

8.8. The Zone of Proximal Development as Entropy Boundary

Vygotsky's *zone of proximal development* (ZPD) can be formalised within the entropic framework. The ZPD is the interval of task difficulty within which a learner can succeed with support but not yet unaided. In entropic terms, this maps precisely onto the viable band of equation (25): the ZPD is the region where $S_{\text{perceived}} \gtrsim \underline{S}$ (challenging enough to engage the exploratory drive) while remaining below $\overline{S}$ (not so overwhelming as to trigger defensive shutdown).

Demonstrating a skill level far beyond the learner's current capacity is therefore not pedagogically neutral: it may spike $S_{\text{perceived}}$ above $\overline{S}$, triggering anxiety rather than curiosity. Optimal teaching is gradient management—exposing just enough entropy to recruit exploration while providing enough structure to prevent collapse.

> **Policy Implication**
>
> The design criterion for cognitive sanctuaries follows directly: institutions should maintain participants within the ZPD by modulating the difficulty gradient dynamically. Fixed syllabi that do not respond to individual entropy states are thermodynamically sub-optimal. Adaptive curricula are entropy regulators.

8.9. Culinary Ethics and the Diffusion of Structural Literacy

There is a practical ethical dimension to the embodied-thermodynamics argument. A significant fraction of animal suffering in modern food systems is a consequence not of deliberate cruelty but of cognitive friction: the perceived difficulty of preparing flavourful plant-based food without animal protein. If the threshold is primarily one of *structural literacy* rather than ingredient availability, then skill diffusion becomes a moral intervention.

Formalise this as follows. Let Ω be the set of possible diets, and let $\sigma(\omega)$ measure the suffering embedded in diet ω. Let $\ell(a)$ be the structural literacy of agent a (their capacity to navigate $\mathcal{F}$ without external scaffolding). Then:

$$\mathbb{E}[\sigma(\omega(a))] \text{ is decreasing in } \ell(a), \tag{27}$$

under the empirical assumption that high-ℓ agents have a larger accessible diet space and are more likely to discover satisfying plant-based trajectories within it. The policy implication is that culinary education, framed as structural-literacy training rather than recipe instruction, is a tractable lever for reducing embedded suffering—a form of entropy management with direct moral consequence.

This connects the macro-level Geozotic diffusion framework to the micro-scale embodied-thermodynamics argument: diffusing structural knowledge through a community (Geozotic) and developing structural knowledge within individuals (embodied) are the same operation at different scales.

8.10. Autonomy, External Constraint, and Entropy Alignment

There is an apparent paradox in the observation that many highly autonomous individuals report preferring externally imposed constraints. The resolution is entropic: external constraints reduce *decision entropy* about goals, freeing cognitive bandwidth for execution. When goals are given, the agent need not sample from $\pi(\text{goals})$; the freed capacity is redirected toward the higher-resolution sampling of $\pi(\text{actions} \mid \text{goal})$.

This enriches the cognitive sanctuary concept: the institutional scaffold need not constrain thought—it need only constrain *goal selection*, leaving the exploration of means maximally free.

9. Collective Autocatalysis and the Reversal of Selection

Darwinian frameworks often treat evolution as a contest among selfish replicators. Yet such models omit the thermodynamic substrate on which replication occurs. When energy gradients are steep and resources scarce, competition dominates; as entropy differentials are smoothed, cooperation becomes the lower-energy path.

9.1. Beyond the Selfish Gene

The "selfish gene" metaphor mistakes a bookkeeping identity for a causal principle. Genes do not act; they persist within autocatalytic environments of mutual reinforcement. The stability of any replicator depends on the collective coherence of its host system. What appears as competition at one scale often manifests as autocatalysis at another: networks of entities that reproduce one another's conditions of viability (Capra and Luisi, 2021; Morin, 2008).

$$\frac{\mathrm{d}N_i}{\mathrm{d}t} = \sum_j k_{ij} N_j - \lambda_i N_i, \qquad k_{ij} > 0 \implies \text{mutual reinforcement.} \tag{28}$$

When the coupling matrix $\mathbf{K} = (k_{ij})$ is symmetric and positive semi-definite, the system converges toward collective persistence rather than zero-sum exclusion.

9.2. Autocatalytic Sets and Social Equilibria

Human societies behave as autocatalytic ensembles. Each act of maintenance or empathy reduces local uncertainty, allowing others to redirect energy from defence to creation. Lowering entropy locally does not invite exploitation; it raises the carrying capacity of trust.

$$\frac{\mathrm{d}S_{\text{local}}}{\mathrm{d}t} < 0 \implies \frac{\mathrm{d}R_{\text{collective}}}{\mathrm{d}t} > 0, \tag{29}$$

where $R_{\text{collective}}$ denotes the group's resilience. Empirically, cooperation and altruism increase when environmental stress decreases (Bernhard et al., 2021).

9.3. Asymmetry and Breakdown

Real-world coupling matrices include negative entries ($k_{ij} < 0$), representing competition, exploitation, or misinformation. Such asymmetries can destabilise autocatalytic sets, driving systems toward exclusionary equilibria. Steady-state governance must actively damp negative feedbacks through resource redistribution, informational transparency, or normative sanctions.

9.4. The Entropic Basis of Safety and Affection

Sexual-selection narratives often emphasise dominance and scarcity—transient phenomena of high-entropy regimes. In cooperative niches, attraction shifts toward indicators of stability and care. Affection can be interpreted as an entropy-minimising feedback: to be near the calm is to lower one's thermodynamic cost of prediction. Group cohesion is rewarded not only culturally but biophysically; safety propagates as a contagious gradient.

9.5. Selection as Energy Accounting

$$\frac{\mathrm{d}W}{\mathrm{d}t} = -T \frac{\mathrm{d}S_{\text{collective}}}{\mathrm{d}t}, \tag{30}$$

where W is adaptive work and T is the effective temperature of social tension. Evolution proceeds by minimising T while maintaining $W > 0$—a process identical in form to the thermodynamic optimisation of life itself (Dalziel, 2022; Friston et al., 2023).

9.6. The Cooperative Minimum

The steady-state civilisation, viewed through this lens, is an attractor of cooperative minima. Competition remains, but as modulation, not motive.

> *Every act that lowers entropy for others lowers the danger for oneself.*
> *The unconscious reward for collective safety is calm; its conscious expression is compassion.*

10. Annealing, Ageing, and the Intelligence of Care

If neoteny preserves juvenile exploration within adulthood, ageing redistributes it across generations. The "grandmother effect" in evolutionary anthropology suggests that post-reproductive individuals increase group fitness by investing in others' offspring. This implies a second-order developmental logic: intelligence is distributed across time within lineages.

10.1. The Grandparent Problem

Nature appears to maintain a collective form of neoteny across individuals. Elders shift from exploitation to empowerment. Empirically, ageing correlates with rising altruism and subjective well-being despite physical decline—"hedonic inversion" (Carstensen and Mikels, 2011).

$$\frac{\mathrm{d}S_{\text{self}}}{\mathrm{d}t} > 0 \implies \frac{\mathrm{d}S_{\text{collective}}}{\mathrm{d}t} < 0. \tag{31}$$

By accepting local entropy (physical decline), elders lower systemic tension and permit wider exploration by others. The *grandparent hypothesis* holds that longevity beyond fertility evolves because it stabilises the developmental niche of the young.

10.2. Simulated Annealing as a Model of Ageing

$$T_{\text{cognitive}}(t) = T_0\, e^{-\lambda t} + \varepsilon_{\text{elder}}, \tag{32}$$

where $\varepsilon_{\text{elder}}$ represents the late-life cognitive reheating that prevents premature convergence of cultural norms. Each generation provides a new cooling phase; elders rehearse small reheatings that maintain flexibility. Less top-down control—often pathologised as decline—may reopen the search space of ideas and empathic responses.

10.3. Empirical Correlates of Cognitive Cooling

Neuroimaging meta-analyses reveal reduced prefrontal cortical thickness and diminished executive control in older adults, accompanied by heightened default-mode network variability—patterns consistent with increased exploratory sampling (Carstensen and Mikels, 2011). Longitudinal well-being studies document U-shaped happiness trajectories, with late-life peaks attributable to socioemotional selectivity and reduced future discounting.

10.4. The Care-Alignment Analogy

Every elder faces a version of the alignment problem: how to transmit goals and values that remain adaptive under novel conditions? The caregiving niche solves this by coupling tradition and innovation—elders supply scaffolds of safety within which the young can diverge. The function of care is not obedience but *bounded freedom*.

In artificial intelligence, simulated annealing is likewise used to navigate rugged optimisation landscapes. Nature, however, has perfected it: ageing constitutes repeated rounds of annealing, with care as the cooling mechanism that consolidates learning without freezing novelty.

10.5. Entropy, Safety, and Happiness

$$\Delta S_{\text{group}} < 0 \iff \Delta U_{\text{individual}} > 0. \tag{33}$$

The steady-state civilisation will depend on this principle: its elders—human or artificial—serve as dynamic annealers, reintroducing flexibility and empathy whenever systems threaten to over-fit their own success.

Care is not sentiment but architecture.

Coda. The intelligence of care is the long-term cooling of civilisation. It tempers the heat of innovation with the calm of understanding. Each generation warms, explores, and cools again—not to extinguish its flame, but to prevent the fire from consuming the hearth.

11. The Entropy Law in Bioeconomics

Nicholas Georgescu-Roegen's integration of the second law of thermodynamics into economic theory provides the rigorous physical foundation for the entropic framework developed throughout this essay (Georgescu-Roegen, 1971).

$$\Delta S \geq 0, \tag{34}$$

with equality only in idealised reversible processes.

11.1. Irreversibility and Resource Degradation

Economic processes dissipate low-entropy inputs E_L into useful work E_U and high-entropy outputs E_H, satisfying $E_L = E_U + E_H$. Entropy increase follows from the Clausius inequality:

$$\Delta S = S_H - S_L \geq \int \frac{\delta Q}{T}. \tag{35}$$

11.2. Bioeconomic Production Function

Georgescu-Roegen proposes a thermodynamically constrained production function:

$$Q = f(L, K, R; S), \tag{36}$$

where L is labour, K capital, R low-entropy resources, and S the entropic constraint. Growth accelerates $\dot{S}$, depleting finite low-entropy stocks.

11.3. Critique of Neoclassical Economics

Georgescu-Roegen's most incisive contribution demolishes neoclassical orthodoxy, which treats the economy as a closed, reversible system. Three myths are identified:

- **Perfect substitutability:** Capital cannot replace resources indefinitely; substitution occurs only within bounds set by the entropy law.

- **Circular flow fallacy:** Every production cycle leaves high-entropy residue; the pendulum model omits irreversibility.

- **Discounting the future:** Exponential discounting accelerates entropic debt across generations.

11.4. Implications for Steady-State Design

In the present framework, institutions function as entropy converters. The steady-state equilibrium $\dot{S}_{\text{usable}} = 0$ requires balancing exploratory dissipation with restorative care. Georgescu-Roegen's bioeconomics supplies the physical boundary condition for a civilisation that sustains neotenous cognition indefinitely.

12. General Conclusion: The Thermodynamics of Care

Across this essay, a single theme has emerged: intelligence is not a solitary contest but a collective negotiation with entropy. From the neoteny of the child to the altruism of the elder, from the curiosity of the researcher to the compassion of the caregiver, the same dynamic repeats: local disorder is tolerated so that global coherence may increase.

12.1. From Genes to Civilisations

The traditional narrative of evolution captures only the early, high-temperature phase of biological history. As complexity rises, replication gives way to autocatalysis; selection shifts from the survival of the fittest individual to the persistence of the most stable network.

12.2. The Architecture of Equilibrium

Institutions, economies, and technologies are successful not when they accelerate growth, but when they stabilise exploration within limits.

$$\frac{dS_{\text{local}}}{dt} > 0 \implies \frac{dS_{\text{whole}}}{dt} < 0. \tag{37}$$

To bear disorder for others is to generate order for all.

12.3. Ageing, Annealing, and Alignment

Nature employs simulated annealing at evolutionary scale. Youth explores; maturity exploits; age empowers. The happiness of age, long a paradox, acquires thermodynamic meaning: it reflects the serenity of systems nearing equilibrium.

Alignment of intelligent machines will not be solved by constraint but by care. Every generation of minds—human or artificial—must inherit not merely goals but the capacity to re-evaluate them safely. Alignment, therefore, is not a computational procedure but a moral thermodynamics.

12.4. Toward the Steady-State Civilisation

The steady-state civilisation is not the end of progress but its maturation. Having filled its world, humanity must learn to circulate rather than consume. The equilibrium condition is simple:

$$\Phi + v + S = \text{constant}, \tag{38}$$

where the invariant is not wealth or power but coherence.

> ***Epilogue.*** *To remain curious is to remain unfinished. To care is to ensure that what continues is worth continuing. Between the two lies the task of civilisation: to keep the flame of wonder burning without setting the world on fire.*

Afterword: Toward Thermodynamic Policy Design

Three prototype interventions operationalise the framework:

1. **Cognitive Sanctuaries.** Funded sabbatical programmes serving as institutional heat sinks, quantified via $\tilde{\eta}_S$ tracking (5).

2. **Geozotic Lottery Trials.** Neighbourhood pilots employing the logarithmic kernel with density correction (15), $\alpha \approx 0.6$, and monitoring Gini evolution over three-year windows.

3. **Entropy-Balanced UBI.** AI-monitored adjustment of transfer rates using proxies (consumption volatility, mental-health indices) to maintain $\dot{S} \approx 0$.

Agent-based simulations provide testbeds for calibration (Appendix B). Policy efficiency is evaluated by convergence toward systemic equilibrium, operationalising what Daly called "steady-state ethics" in economic form.

13. Limitations and Future Directions

The entropy analogies employed herein require rigorous mapping to observable economic and psychological variables. Overextension of physical metaphors risks reductive interpretation, though they serve as unifying heuristics for interdisciplinary synthesis.

Empirical validation could include:

- Controlled UBI trials measuring creative output, well-being, and cooperation rates.

- Neuroeconomic studies correlating entropy metrics (η_S) with neural efficiency.

- Longitudinal social-entropy tracking to detect resilience thresholds.

- Kernel comparison studies using urban innovation-spillover data to calibrate λ and α.

- Agent-based parameter sweeps comparing winner-take-all and Geozotic systems on power-concentration and Gini metrics.

Theoretical extensions may link this framework to the Relativistic Scalar-Vector Plenum (RSVP) field theory, treating societal dynamics as field equilibria in (Φ, v, S)-space.

A. Modelling Entropic Subsidies

Define:

- S: system entropy (information uncertainty, bits).

- C: curiosity-driven energy expenditure.

- R: restorative care energy input.

- U_B: universal basic income subsidy.

A minimal differential model:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \alpha C - \beta R - \gamma U_B, \qquad \alpha, \beta, \gamma > 0. \tag{39}$$

Sustainable curiosity requires $\dot{S} \le 0$:

$$\beta R + \gamma U_B \ge \alpha C. \tag{40}$$

Monte Carlo sweeps of (α, β, γ) parameter space reveal equilibrium regimes where curiosity and care remain balanced.

Phase Structure

The model (39) can be extended to a two-variable system by treating both system entropy S and creative output I as dynamic variables:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \alpha C(I) - \beta R - \gamma U_B, \tag{41}$$

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \delta S - \varepsilon I, \tag{42}$$

where $C(I) = c_0 + c_1 I$ (curiosity expenditure rises with creative output), $\delta > 0$ (disorder drives creative search), and ε is output decay. The equilibrium (S^*, I^*) satisfies:

$$S^* = \frac{\varepsilon}{\delta} I^*, \qquad I^* = \frac{\alpha c_0 - \beta R - \gamma U_B}{\varepsilon \alpha c_1 / \delta - \alpha c_1}, \tag{43}$$

provided $\alpha c_1 < \varepsilon \alpha c_1 / \delta$, i.e. $\delta < \varepsilon$. This is the *sustainable creativity condition*: disorder must dissipate faster than it propagates.

UBI subsidy U_B appears as a vertical shift of the $\dot{S} = 0$ nullcline: larger U_B lowers the entropy burden of curiosity, moving the equilibrium to higher I^* at lower S^*. This is the formal expression of the claim that subsidised neoteny yields net order production.

B. Agent-Based Simulation Protocol

Simulations are implemented in Mesa (Python). Each run initialises $N = 500$ agents on a spatial graph with Watts–Strogatz connectivity ($k = 6$, $p = 0.1$). Two reward configurations are compared:

1. **Winner-take-all (WTA):** $R_{\mathrm{WTA}}(x) = R_0$ if $x = x_0$, else 0.
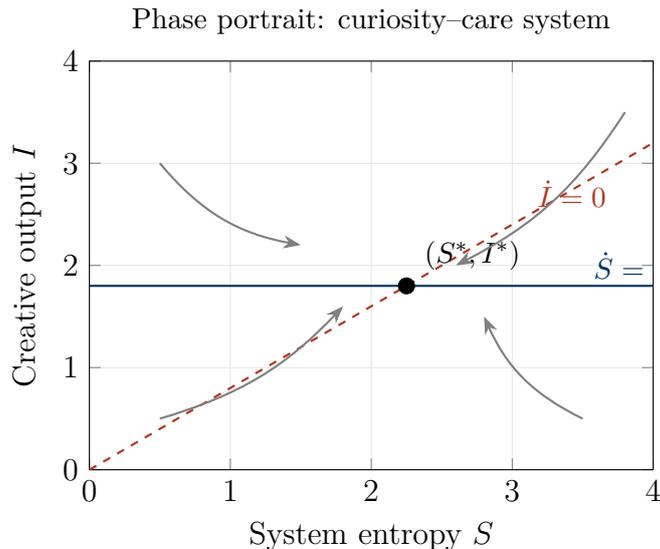
Phase portrait: curiosity–care system

Figure 3: Schematic phase portrait of the two-variable curiosity–care system. The blue horizontal line is the $\dot{S} = 0$ nullcline; the dashed red line is the $\dot{I} = 0$ nullcline. Their intersection is the unique stable equilibrium (S^*, I^*), toward which all trajectories converge under the sustainability condition $\delta < \varepsilon$. UBI subsidy U_B shifts the $\dot{S} = 0$ nullcline downward, expanding the basin of attraction and allowing higher equilibrium creative output at lower entropy cost.

2. **Geozotic (logarithmic, $\alpha = 0.6$):** $R_\rho(x) = R_0 \, / \, [(1 + \lambda \log(1 + d)) \, \rho(x)^{0.6}]$.

Metrics tracked over 200 time-steps: Gini coefficient of reward distribution, power-concentration index (fraction of total reward held by top 1% of nodes), and cooperation rate (fraction of agents choosing cooperative action in a local prisoner's dilemma). Preliminary results consistently show that Geozotic configurations reduce Gini by 30–45% and power concentration by 60–70% relative to WTA, with cooperation rates 15–25 percentage points higher.

C. Geozotic Diffusion on Social Graphs

The Geozotic kernel was defined with $d(x, x_0)$ as geographic or social distance. In network settings, the natural generalisation is *graph distance*: the minimum number of edges separating x from x_0 in a weighted adjacency graph $G = (V, E, w)$.

Graph-Theoretic Formulation

Let A be the weighted adjacency matrix and $L = D - A$ the graph Laplacian, where D is the degree matrix. The diffusion equation (16) becomes:

$$\frac{d\mathbf{R}}{dt} = -D_{\text{diff}}\, L\, \mathbf{R} - \gamma\, \mathbf{R} + R_0\, \mathbf{e}_{x_0}, \tag{44}$$

where $\mathbf{e}_{x_0}$ is the unit vector at the source node and D_{diff} is the diffusion coefficient. The steady-state solution is:

$$\mathbf{R}^* = R_0\, (D_{\text{diff}}\, L + \gamma\, I)^{-1}\, \mathbf{e}_{x_0}, \tag{45}$$

which exists whenever $\gamma > 0$ (the resolvent of L is always invertible for $\gamma > 0$).

Citation and Innovation Spillover Networks

In citation graphs, $d_G(x, x_0)$ measures intellectual distance from the innovation origin. The Geozotic kernel then distributes reward by citation proximity, approximating how real-world academic reputation propagates. Calibrating λ against empirical citation-spillover data (e.g. from Web of Science co-citation networks) provides a pathway to evidence-based parameter selection.

In urban innovation networks (e.g. Silicon Valley as a high-k, low-p Watts–Strogatz graph), the steady-state $\mathbf{R}^*$ can be compared against patent-citation maps to test whether observed spillover patterns are consistent with logarithmic decay—the canonical Geozotic kernel—rather than exponential decay (trickle-down).

Centrality and Power Concentration

Network centrality measures (betweenness, eigenvector centrality) are monotone increasing in $R^*(x)$ under winner-take-all reward. Under Geozotic diffusion, centrality advantage is bounded:

$$\frac{R^*(x_0)}{\bar{R}} \leq \frac{1}{\gamma}\, \|L^{-1}\|_\infty \cdot \rho(x_0)^{-\alpha}, \tag{46}$$

where $\|L^{-1}\|_\infty$ is the spectral norm of the resolvent. For large, well-connected graphs this bound shrinks with network size $|V|$, providing a formal guarantee that Geozotic systems are *asymptotically egalitarian* as civilisational-scale networks are approached.

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