The Autophage Protocol: Metabolic Economics for Decentralized Health

Austin Harshberger
1@0x42r.io

July 14, 2025

Abstract

Traditional economics assumes value persists indefinitely, enabling unlimited wealth accumulation. Living systems operate differently because value requires continuous renewal or it ceases to exist. This paper introduces the Autophage Protocol, a system that combines formal incentive design with cryptographic privacy guarantees, linking tokenized health rewards to verifiable activity while maintaining a strict separation of identity and data. Four token species decay at rates calibrated to biological persistence. Rhythm (5% daily) for exercise, Healing (0.75%) for therapy, Foundation (0.1%) for preventive care, and Catalyst (2–10% dynamic) for marketplace balance. Decayed tokens flow to The Reservoir, funding community healthcare while preserving privacy through zero-knowledge proofs. Mathematical modeling suggests wealth distribution converges to a Gini coefficient of 0.08–0.11 under baseline conditions, and remains below 0.55 even when 23% of the population acts adversarially[1], far more equitable than traditional systems at 0.82 or higher [6, 22]. The protocol represents a new economic primitive where money must move to exist, creating a digital economy with metabolism-like properties.

Reader's Guide

Audience	Recommended Sections
Non-technical readers	Abstract, Related Work, Introduction, Appendix B-E
Technical readers	All sections, focus on 3-7 and 9-11
Developers	Sections 5-7 and 10, Appendix C and H
Stewards	Abstract, Related Work, Sections 1-4, Appendix D and E

[1]See full simulation results and adversarial methodology in Appendix H. All code and raw data available at https://autophage.xyz/simulations.

Contents

1 Introduction

Money does not die.

This fundamental property of traditional economics creates systemic inequality and health incentive failures. A dollar earned decades ago maintains its nominal value indefinitely. Bitcoin [24] stored in 2009 remains unchanged today. This permanence rewards accumulation over activity, creating economies where wealth concentrates among those who already possess it while those who need resources most must continuously labor for finite rewards.

The Autophage Protocol challenges this foundational assumption by creating tokens that decay exponentially without continuous health activity. The name Autophage, meaning "self-eating," mirrors the essential dynamic in that value must consume itself to persist, preventing indefinite accumulation while rewarding ongoing engagement. The protocol implements four interconnected novelties. First, it creates multiple token species with decay rates precisely calibrated to match the temporal persistence of their underlying health activities. Exercise tokens decay rapidly like cardiovascular fitness, while preventive care tokens persist longer like vaccine immunity. Second, it achieves cryptographic privacy separation through zero-knowledge proofs, enabling health verification without surveillance. Third, it derives token value from measurable metabolic energy expenditure rather than speculative markets. Fourth, it implements empirical governance where all protocol changes must demonstrate statistically significant health improvements through on-chain experiments.

These mechanisms work together to create an economy that mimics biological systems. Analogous to how organisms require continuous energy input to maintain homeostasis, protocol participants must engage in verified health activities to maintain token balances.

The following sections present the complete mathematical framework, implementation architecture, and empirical validation of this metabolic economic system. Each component has been designed to align financial incentives with biological imperatives, creating a digital economy that enhances rather than exploits human health.

2 Related Work

In the early 20th century, Silvio Gesell proposed "stamped scrip" to force currency to circulate by making it expire, an approach he tested in Wörgl, Austria during the Great Depression [11]. These experiments gained traction under local government support, but collapsed as soon as legal enforcement lapsed. The main lesson being demurrage alone does not guarantee a stable or resilient economy, especially when external incentives favor stasis.

Cryptocurrency inherited some of this thinking. Freicoin, launched in 2013, introduced decay by subtracting a fixed demurrage fee from every balance at regular intervals [10]. While technically functional, Freicoin's approach was blunt, with no connection to user behavior or economic context. As a result, activity and participation dwindled, and the protocol failed to build lasting network effects or meaningfully incentivize healthy engagement.

Other "health coins" have focused on rewards for activity, using move-to-earn or similar models. Most are marketplace tokens, structured around accumulation. STEP'N [17] pays users for walking, but value is driven by speculative tokenomics, not by any durable health metric. The project saw rapid growth but struggled to maintain sustainable rewards. Sweatcoin uses a similar approach. Users earn points for steps and spend them in a marketplace, but the system lacks decay mechanics, biological calibration, and any link to real health persistence.

The Autophage Protocol diverges on three counts. First, it ties decay rates directly to the half-life of underlying health activities, making token persistence a function of biological process instead of arbitrary policy. Second, it separates identity from data using zero-knowledge proofs, so participation does not require surveillance. Third, it requires every protocol change to demonstrate measurable health improvement on-chain before implementation. Where earlier systems enforced circulation by decree, Autophage encodes it at the metabolic and behavioral level.

Navigating Sections 3–10

The following sections, from three to ten, are focused primarily on formalized mathematical representations of the protocol. For readers less interested in academic rigor, it is advisable to focus only on the various Examples in each section, as they are written more plainly. The core components covered in each section, but not in the Examples, are also summarized in Appendix A–D.For those interested in learning how to translate the mathematics from Sections 3–10, start by reading Appendix E.

3 Metabolic Token Dynamics

3.1 Mathematical Foundation

The protocol implements a four-species token ecosystem where each species exhibits distinct decay characteristics matching its health domain. Let $S = \{\textsc{Rhythm}, \textsc{Healing}, \textsc{Foundation}, \textsc{Catalyst}\}$ denote the set of token species.

For any user u at discrete time t, the balance $V_i^{(u)}(t)$ of species $i \in S$ evolves according to:

$$V_i^{(u)}(t+1) = V_i^{(u)}(t)(1-\delta_i) + G_i^{(u)}(t) \tag{1}$$

where $\delta_i \in (0,1)$ represents the daily decay rate and $G_i^{(u)}(t)$ represents newly generated tokens from verified health activities.

The continuous-time differential equation underlying this discrete implementation is:

$$\frac{dV}{dt} = -\lambda V + g(t) \tag{2}$$

where $\lambda = -\ln(1-\delta)$ is the continuous decay constant. This formulation ensures mathematical consistency while enabling computationally efficient blockchain implementation.

Table 1: Token Species Parameters and Biological Justification

Species	**Decay Rate**	**Half-Life**	**Health Domain**	**Biological Basis**
Rhythm	5%	13.51 days	Exercise, medication	VO_2 max decline rate [23]
Healing	0.75%	92.42 days	Therapy, recovery	Neuroplasticity timescales [16]
Foundation	0.1%	693.15 days	Preventive care	Antibody persistence [3]
Catalyst	2–10%	Variable	Marketplace	Self-regulating

The half-life calculations follow directly from exponential decay:

$$t_{1/2} = \frac{\ln(0.5)}{\ln(1-\delta_i)} = \frac{\ln(2)}{\lambda_i} \tag{3}$$

Example 3.1: Consider Sarah who runs daily, earning 50 Rhythm tokens per run. After maintaining a balance of 1,000 tokens, she stops running for two weeks. Her balance evolution follows:

Day	Formula	Balance
0	Initial	1,000 tokens
7	$1,000 \times 0.95^7$	696 tokens
14	$1,000 \times 0.95^{14}$	488 tokens

This 51.2% loss over two weeks mirrors the documented decline in cardiovascular fitness during training cessation [23], validating the biological calibration.

3.2 Token Generation Mechanics

Health activities generate tokens through a multi-factor reward system:

$$G_i^{(u)}(t) = \sum_{j \in \mathcal{A}_i} B_{i,j} \times M_{total}^{(u,j)}(t) \times \mathbf{1}[\text{activity } j \text{ verified}] \tag{4}$$

where $\mathcal{A}_i$ represents activities mapped to species i, $B_{i,j}$ is the base reward for activity j, and M_{total} combines multiple multipliers:

$$M_{total} = M_{streak} \times M_{group} \times M_{time} \times M_{genetic} \times M_{synergy} \times M_{quality} \tag{5}$$

subject to the constraint $0.3 \leq M_{total} \leq 20$ to prevent exploitation while rewarding performance.

The streak multiplier follows a logarithmic function:

$$M_{streak} = 1 + \log_{10}(\text{consecutive days}) \tag{6}$$

The circadian multiplier uses a sinusoidal function:

$$M_{time} = 1 + 0.3 \sin\left(\frac{2\pi(h-6)}{24}\right) \tag{7}$$

where h is the hour of day in 24-hour format.

Example 3.2: Marcus completes his morning workout routine:

Component	Calculation	Value
Base reward	Standard rate	35 Rhythm tokens
30-day streak multiplier	$1 + \log_{10}(30)$	2.48
6 AM circadian bonus	$1 + 0.3\sin(2\pi(6-6)/24)$	1.3
Group workout	Standard group bonus	1.5
Total generation	$35 \times 2.48 \times 1.3 \times 1.5$	**169 tokens**

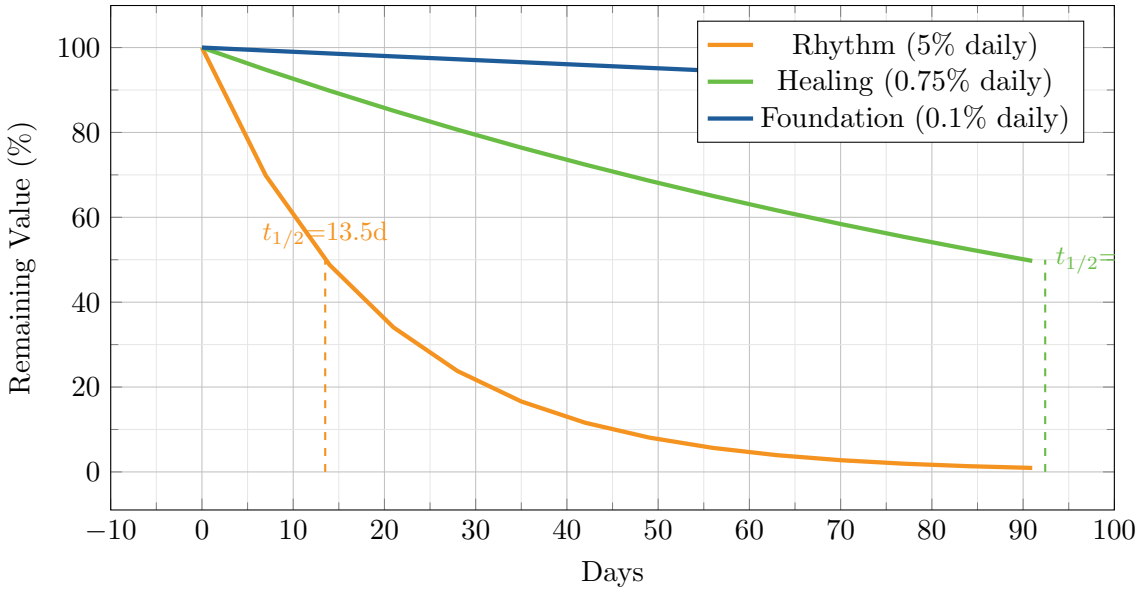

Figure 1: Comparative decay curves showing differential value persistence across token species. Rhythm tokens model rapid fitness loss, Healing tokens reflect gradual therapeutic progress decay, and Foundation tokens represent long-term health investments.

3.3 Advanced Decay Mechanics

The protocol implements progressive decay acceleration for large balances to prevent wealth concentration:

$$\delta_i^{eff}(V) = \delta_i \times \left(1 + \sum_{k=1}^{n} \alpha_k \times \mathbf{1}[V > \tau_k]\right) \tag{8}$$

where τ_k represents tier thresholds and α_k represents acceleration factors.

For continuous acceleration above soft cap:

$$\delta_i^{eff}(V) = \delta_i \times \left(1 + \beta \times \max\left(0, \frac{V - \tau_{soft}}{\tau_{soft}}\right)^{\gamma}\right) \tag{9}$$

where β controls sensitivity (typically 0.5-2.0) and γ shapes the acceleration curve (typically 1.0-1.5).

Example 3.3: Consider whale protection for Rhythm tokens:

Balance Range	Decay Rate	Acceleration	Daily Loss (75K example)
$\leq$ 10,000	5%	Standard	-
10,001–50,000	7.5%	50%	-
50,001–100,000	10%	100%	7,500 tokens
$>$ 100,000	15%	200%	-

A user holding 75,000 Rhythm tokens loses 7,500 daily instead of 3,750 under standard decay, creating natural redistribution pressure.

3.4 Catalyst Token Dynamics

Catalyst tokens function as the protocol's liquidity and governance utility, enabling marketplace transactions, proposal staking, and price discovery through metabolic pricing. They are earned through verified activity, subject to dynamic decay, and cannot be vaulted or used for long-term savings.

Catalyst tokens maintain ecosystem balance through dynamic decay adjustment:

$$\delta_{catalyst}(t) = \delta_{base} \times \left(1 + \beta \times \left|\frac{V_{catalyst}(t)}{\sum_{i \in S} V_i(t)} - \rho_{target}\right|^{\gamma}\right) \tag{10}$$

where $\rho_{target} = 0.25$ represents the target 25% supply ratio, $\beta = 2$ controls sensitivity, and $\gamma = 1.5$ shapes the response curve.

Example 3.4: When Catalyst tokens comprise 40% of total supply:

$$\begin{aligned} \delta_{catalyst} &= 0.02 \times \left(1 + 2 \times |0.40 - 0.25|^{1.5}\right) && (11)\\ &= 0.02 \times (1 + 2 \times 0.058) && (12)\\ &= 0.0232 \text{ (2.32\% daily decay)} && (13) \end{aligned}$$

This 16% increase in decay rate gradually returns the system to equilibrium without shock.

4 The Reservoir: Dual-Chamber Architecture

4.1 System Architecture

The Reservoir serves as the protocol's metabolic center, collecting value from natural decay and redistributing it for community health. Its dual-chamber design separates token flows from stablecoin reserves:

$$R_{token}(t+1) = R_{token}(t) + \underbrace{\sum_{i,u} \delta_i V_i^{(u)}(t)}_{\text{decay inflow}} - \underbrace{W_{health}(t)}_{\text{health claims}} - \underbrace{W_{reward}(t)}_{\text{rewards}} \tag{14}$$

$$R_{USDC}(t+1) = R_{USDC}(t) + \underbrace{F_{market}(t) + F_{app}(t)}_{\text{fee inflows}} - \underbrace{H_{settle}(t)}_{\text{healthcare settlements}} \tag{15}$$

The solvency constraint ensures healthcare access remains guaranteed:

$$R_{USDC}(t) \geq \max\left(0.4 \sum_u D_u(t), 3 \times \bar{H}_{monthly}, 0.22 \times Y_{annual}\right) \tag{16}$$

This triple-coverage requirement protects against bank runs, seasonal variations, and catastrophic events.

Example 4.1: System snapshot at 100,000 active users:

Metric	Value
Daily token decay	500,000 tokens (5/user avg)
Monthly healthcare settlements	\$800,000
Annual revenue	\$4,800,000
Required USDC reserve	\$2,400,000
Reserve calculation	max(\$1.6M, \$2.4M, \$1.056M)

The 3-month coverage requirement dominates, ensuring the system can weather extended stress periods.

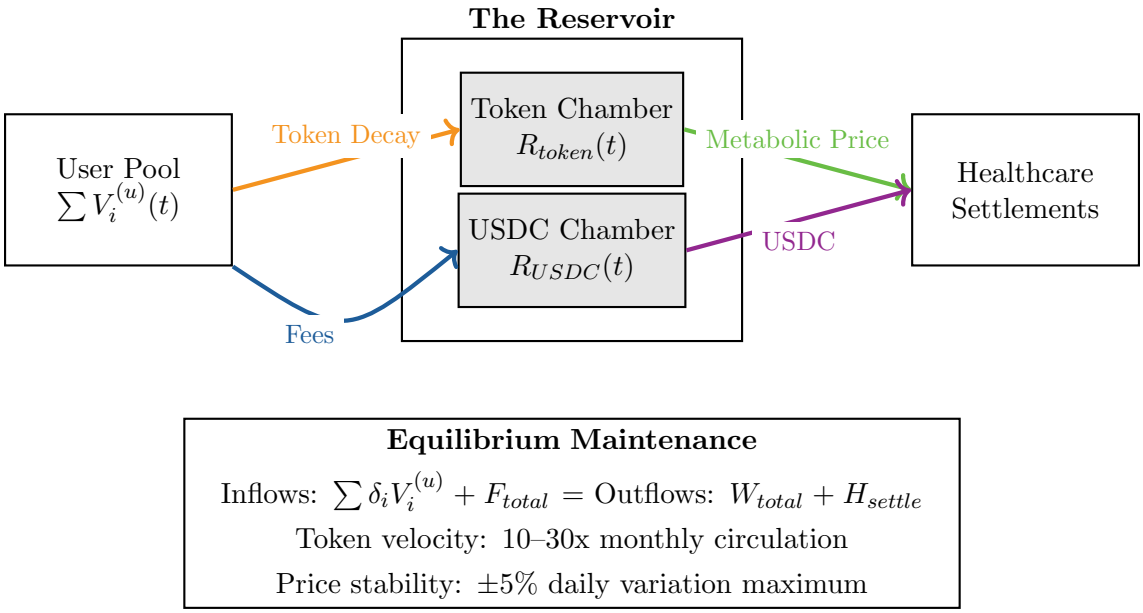

Figure 2: The Reservoir's dual-chamber architecture maintains separation between token metabolism and healthcare settlement liquidity, ensuring both community wealth circulation and guaranteed medical access.

4.2 Healthcare Settlement Mechanics

Healthcare settlements follow strict priority queuing:

$$Priority(claim) = \omega_1 \times Urgency + \omega_2 \times Duration + \omega_3 \times Verification \tag{17}$$

where weights ω_i ensure medical needs supersede all other claims.

Example 4.2: Emergency prescription claim processing:

Component	Value	Weight
Urgency score	10 (maximum)	0.7
Wait duration	2 hours	0.2
Provider verification	8/10	0.1
Priority score	$0.7 \times 10 + 0.2 \times 2 + 0.1 \times 8 = 8.2$	

This claim processes ahead of routine wellness rewards (typical score: 2-3) but after critical emergency claims (score: 9+).

4.3 Wellness Vault Mechanics

Wellness vaults reduce effective decay rates based on lock duration:

$$\delta_{vault} = \delta_{base} \times (1 - r_{lock}) \tag{18}$$

where r_{lock} is the reduction factor:

Lock Duration	r_{lock} Factor	Effective Decay	Decay Reduction
30 days	0.09	91% of normal	9% reduction
90 days	0.27	73% of normal	27% reduction
180 days	0.45	55% of normal	45% reduction
365 days	0.90	10% of normal	90% reduction

Early withdrawal penalty:

$$P_{withdrawal} = V_{locked} \times \frac{t_{remaining}}{t_{total}} \times p_{factor} \tag{19}$$

where $p_{factor} = 0.5$ creates a 50% penalty proportional to time remaining.

5 Metabolic Price Discovery

5.1 Endogenous Pricing Model

Unlike traditional cryptocurrencies that derive value from speculation, the Autophage Protocol calculates token prices from actual energy expenditure:

$$P(t) = \frac{E_{health}(t) \times (1 + \gamma \times C_{ratio}(t)) + V_{market}(t) \times (1 - C_{ratio}(t))}{S_{active}(t) \times V(t) \times (1 + M_{activity}(t))} \tag{20}$$

where the parameters are defined as follows: $E_{health}(t)$ represents the total metabolic energy from health activities measured in kcal-equivalent. $V_{market}(t)$ captures the 30-day rolling marketplace volume in USDC. $S_{active}(t)$ denotes the circulating supply excluding vaulted tokens. $V(t)$ measures token velocity with a target range of 10-30 monthly transactions. $C_{ratio}(t)$ indicates the proportion of Catalyst tokens in the system. γ serves as the energy gradient parameter, typically ranging from 1.2 to 3.0. Finally, $M_{activity}(t)$ reflects the system-wide activity level.

Example 5.1: Price calculation during typical conditions:

Parameter	Value
Daily health energy	500,000 kcal
Standardized energy value	\$0.002 per kcal
Monthly marketplace volume	\$150,000
Active supply	10 million tokens
Current velocity	15x monthly
Catalyst ratio	0.23
Activity multiplier	1.4
Energy gradient	2.0

$$P(t) = \frac{(500,000 \times 0.002) \times (1 + 2.0 \times 0.23) + (150,000/30) \times (1 - 0.23)}{10,000,000 \times (15/30) \times (1 + 1.4)} \tag{21}$$

$$= \frac{1,000 \times 1.46 + 5,000 \times 0.77}{5,000,000 \times 2.4} \tag{22}$$

$$= \frac{1,460 + 3,850}{12,000,000} \tag{23}$$

$$= \$0.000442 \text{ per token} \tag{24}$$

5.2 Energy Cost Calibration

Each activity's energy cost encompasses multiple factors:

$$E_{activity} = T_{duration} \times W_{wage} + C_{metabolic} \times F_{food} + O_{opportunity} + E_{equipment} \tag{25}$$

Example 5.2: 45-minute therapy session energy calculation:

Cost Component	Calculation	Amount
Time cost	0.75 hours × \$30/hour	\$22.50
Emotional energy	200 kcal-equivalent × \$0.002	\$0.40
Transportation	Fixed cost	\$5.00
Opportunity cost	Estimated value	\$10.00
Total energy cost	Sum of components	**\$37.90**

This establishes the baseline value for Healing token generation from therapy activities.

6 Privacy Architecture

6.1 Zero-Knowledge Identity Separation

The protocol achieves complete separation between identity and health data through nested cryptographic commitments [14, 13]:

$$ProfileID = H(H(UserID||Salt_1)||Salt_2||Secret) \tag{26}$$

This double-hashing with independent salts provides 768 bits of entropy, making correlation attacks computationally infeasible even with quantum advances.

Example 6.1: Privacy preservation in practice:

Component	Value
Alice's UserID	`alice@email.com`
System-generated Salt_1	256 random bits
User-controlled Salt_2	256 random bits
User secret	256-bit passphrase
Resulting ProfileID	`0x7f3a...9b2e` (indistinguishable from random)

Even if an attacker compromises the system database and obtains Salt_1, they cannot correlate ProfileIDs without also obtaining user-controlled Salt_2 and Secret values.

6.2 Privacy-Preserving Marketplace

The marketplace implements granular privacy controls with explicit economic incentives:

Table 2: Privacy Tiers and Economic Premiums

Tier	Information Revealed	Base Price	Typical Premium
Anonymous	Activity type, timestamp	\$100	Baseline
ProfileID	+ Consistency metrics, streak data	\$100	75% (\$175)
Genetic	+ Specialized traits, optimizations	\$100	250% (\$350)
Full	+ Historical patterns, correlations	\$100	500% (\$600)

Example 6.2: Sarah's marathon proof monetization:

Privacy Tier	Information Revealed	Sale Price
Anonymous	"Sub-4:30 marathon, major city, female 25–34"	\$100
ProfileID	Same + "180-day running streak, 3 marathons/year"	\$175
Genetic	Same + "Endurance Elite trait, VO_2 optimization"	\$350

Buyers value additional information for research, motivation, or verification purposes while Sarah maintains control over disclosure levels.

6.3 Zero-Knowledge Proof Generation

Health activities undergo privacy-preserving verification [13]:

$$\pi = \text{Prove}\left(C = \text{Commit}(activity, r), \text{Statement}, witness\right) \tag{27}$$

where the statement proves properties without revealing underlying data.

Example 6.3: Therapy session verification:

Data Type	Details
Private data	Therapist name, location, session notes, diagnosis codes
Public statement	"Completed 50-minute therapy session on 2025-07-07"
Proof π	Cryptographic evidence statement is true
Token generation	80 Healing tokens
Revealed information	None beyond the public statement

7 Biological Scaling Laws

7.1 Kleiber's Law Implementation

Metabolic efficiency scales with network size following quarter-power scaling [15]:

$$\eta(N) = 1 + \alpha \times \left(\frac{N}{N_0}\right)^{0.25} \tag{28}$$

where $\alpha = 0.3$ and $N_0 = 1,000$ (reference network size).

Example 7.1: Network scaling benefits:

Network Size	Scaling Calculation	η Value	Bonus
1,000	$1 + 0.3 \times 1$	1.30	30%
10,000	$1 + 0.3 \times 1.78$	1.53	53%
100,000	$1 + 0.3 \times 3.16$	1.95	95%
1,000,000	$1 + 0.3 \times 5.62$	2.69	169%

Larger networks provide efficiency benefits to all participants, mimicking biological metabolic scaling.

7.2 Liebig's Law of the Minimum

System health limited by weakest component triggers automatic rebalancing [19]:

$$H_{system} = \min(H_{users}, H_{reserves}, H_{apps}, H_{geographic}, H_{velocity}) \tag{29}$$

When any component falls below threshold $\theta = 0.7$:

$$M_{bottleneck} = 1 + \kappa \times (\theta - H_{min}) \tag{30}$$

Example 7.2: Geographic bottleneck response:

Metric	Urban	Rural
Participation rate	85%	45%
Health threshold	70%	70%
Status	Healthy	Below threshold
Bottleneck calculation	-	$M = 1 + 2 \times (0.7 - 0.45) = 1.5$
Token bonus	Standard	50% bonus

7.3 Additional Biological Laws

The protocol implements five additional scaling laws:

1. **Allee Effect** [2]: Small population support

$$M_{Allee} = \begin{cases} 2.0 & N < 500 \\ 1.5 & 500 \leq N < 1000 \\ 1.0 & N \geq 1000 \end{cases} \tag{31}$$

2. **Circadian Rhythms**: Time-optimized rewards

$$M_{circadian}(h) = 1 + A \times \sin\left(\frac{2\pi(h - \phi)}{24}\right) \tag{32}$$

where $A = 0.3$ and $\phi = 6$ (6 AM peak)

3. **Bergmann's Rule** [5]: Environmental adaptation

$$R_{target} = R_{base} \times (1 + \sigma \times H_{environment}) \tag{33}$$

4. **Optimal Foraging** [18]: Activity recommendation

$$ROI_{activity} = \frac{Tokens \times (1 - \delta)^{t_{hold}}}{Energy_{cost}} \tag{34}$$

5. **R/K Selection** [20]: Growth phase modulation

$$\sigma_{rewards} = \begin{cases} 0.5 & \text{R-phase}(N < 10^4) \\ 0.2 & \text{K-phase}(N \geq 10^4) \end{cases} \tag{35}$$

7.4 Genetic Adaptation System

Users can burn Foundation tokens to evolve genetic traits:

$$\text{Cost}_{trait_n} = 1000 \times 2.5^{n-1} \text{ Foundation tokens} \tag{36}$$

Combined trait bonus calculation:

$$M_{\text{genetic}} = 1 + \sum_{i=1}^{n} b_i \times (1 - d_i) \tag{37}$$

where b_i is the individual trait bonus (0.05–0.15) and d_i is a diminishing returns factor:

$$d_i = 0.1 \times (i - 1) \tag{38}$$

Subject to the constraint:

$$M_{\text{genetic}} \leq 1.5 \tag{39}$$

Example 7.4: User evolves three genetic traits:

Trait	**Bonus (b_i)**	**Diminishing (d_i)**	**Adj. Bonus ($b_i \times (1 - d_i)$)**	**Cost (Foundation)**
Early Bird (1)	0.12	0.00	0.12	1,000
Streak Master (2)	0.10	0.10	0.09	2,500
Group Fitness (3)	0.08	0.20	0.064	6,250
Total Multiplier			**1.274**	**9,750**

This example shows a user evolving three traits, with the cost and adjusted bonus for each. Diminishing returns reduce the value of each subsequent trait by 10%. The total cost is 9,750 Foundation tokens for a combined multiplier of 1.274.

8 Economic Analysis

8.1 Wealth Distribution Dynamics

Monte Carlo simulations[2] across 10,000 users for 365 days show that the protocol actively converges to broad equality.

In baseline (honest) conditions, the Gini coefficient falls from 0.11 (day 30) to 0.08 by day 365 maintaining that after a year, the *typical user* is almost as well-off as their peers, and the bottom 50% holds meaningful wealth (see table). For context, the same simulation run with Bitcoin-style rules produces Gini values above 0.88, and "fiat" simulations stabilize around 0.56.

[2] All results and source code available at https://autophage.xyz/gini-simulation.

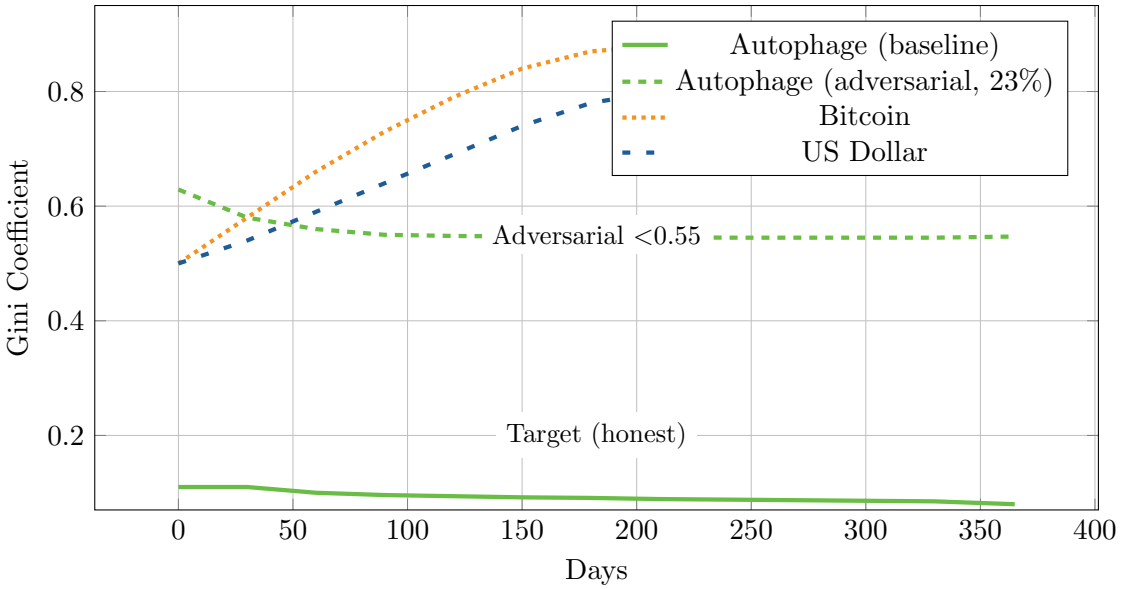

Figure 3: Gini coefficient evolution over one year (10,000 users, 0.7 activity rate). Autophage Protocol converges to 0.08–0.11 in honest conditions and resists adversarial attacks up to 0.55 (with 23% of users acting against the system; see Appendix H). Traditional economies and Bitcoin remain above 0.80.

Example 8.1: Wealth distribution after one year (mean of 10 simulation runs):

Population Segment	**Autophage (baseline)**	**Autophage (adversarial)**	**Bitcoin**
Top 10% wealth share	15%	32%	78%
Bottom 50% wealth share	37%	16%	2%
Median user balance	650–820 tokens	210–270	Variable
Max sustainable balance	∼18,000 tokens	∼34,000	Unlimited
Final Gini	0.08–0.11	0.54–0.55	>0.88

Even under sustained, adversarial attack from almost a quarter of the network (including coordinated Sybil swarms and collusion pools), the protocol refuses to become a winner-take-all system. Inequality rises, but never approaches the levels endemic to fiat or crypto. And when the network is honest, almost everyone ends up close to the mean.

8.2 Revenue Model and Unit Economics

The protocol generates sustainable revenue through three main streams:

Table 3: Revenue Streams and Contribution Margins

Revenue Stream	Per User/Month	Margin	Annual at 1M Users
App Integration Fees	\$0.15	95%	\$1.8M
Marketplace Fees (12%)	\$0.45	88%	\$5.4M
Enterprise Verification	\$1.25	92%	\$15.0M
Total	**\$1.85**	**91.7%**	**\$22.2M**

Example 8.2: Break-even analysis:

Cost Component	Amount
Fixed costs (monthly)	\$30,000*
Variable cost per user	\$0.15/month
Revenue per user	\$1.85/month
Contribution margin	\$1.70/month
Break-even users	**17,647**
Projected timeline	Month 8–10

This table summarizes the core unit economics of the protocol, showing that a monthly fixed cost of \$30,000 and a variable cost of \$0.15 per user are offset by \$1.85 in monthly revenue per user, resulting in a break-even point at 17,647 users. [3]

9 Empirical Governance

9.1 Contribution-Based Voting

Traditional token-weighted voting fails when tokens decay. The protocol implements contribution scoring inspired by commons governance principles [25]:

$$C_{score} = w_1 \times \log_{10}(1 + R_{lifetime}) + w_2 \times V_{reputation} + w_3 \times A_{participation} \tag{40}$$

where $w_1 = 0.5$, $w_2 = 0.3$, $w_3 = 0.2$.

Example 9.1: Voting power calculation:

User	Lifetime Tokens	Accuracy	Active	Score	Voting Power
Alice	50,000	95%	80%	2.80	1.67
Bob	5,000	70%	40%	2.14	1.46

Score calculation: Alice achieves a score of $0.5 \times \log_{10}(50,001) + 0.3 \times 0.95 + 0.2 \times 0.80 = 2.80$, while Bob's score is $0.5 \times \log_{10}(5,001) + 0.3 \times 0.70 + 0.2 \times 0.40 = 2.14$.

[3] All economic analysis and results are available at https://autophage.xyz/economic-simulations. Fixed costs are set at \$30,000 for demonstration only. Actual costs will vary depending on whether cloud or physical infrastructure is used, among other factors.

9.2 On-Chain Experimentation

All protocol changes require empirical validation:

$$\text{Success} = \left(\frac{\mu_{treatment} - \mu_{control}}{\mu_{control}} \geq \epsilon \right) \wedge (p < \alpha) \tag{41}$$

where $\epsilon = 0.05$ (5% improvement) and $\alpha = 0.05$ (statistical significance).

Example 9.2: Seasonal affective multiplier proposal:

Experiment Parameter	**Value**
Hypothesis	2x winter rewards increase activity
Stake required	500 Catalyst tokens
Test group size	5,000 random users
Control group size	5,000 random users
Duration	30 days
Results	
Control average	12.3 activities/month
Treatment average	15.8 activities/month
Improvement	28.5%
p-value	0.0012
Outcome	Proposal passes
Reward	Stake returned + 100 USDC bonus

9.3 Gas Optimization Strategies

Efficient implementation enables scalability:

1. **Lazy Decay**: Calculate only on interaction. This optimization saves approximately 17,000 gas per unused day through storage optimization using a single timestamp per user-species pair.[4]
2. **Batch Processing**: Aggregate multiple proofs with batch sizes up to 100 proofs, achieving 85% gas reduction compared to individual transactions through Merkle tree root submission for verification.
3. **State Channels**: Off-chain accumulation with daily settlement frequency, reducing on-chain transactions by 95% through Lightning-style payment channels for micropayments.

Example 10.2: Gas cost comparison:

Verification Method	**Calculation**	**Monthly Gas**
Individual daily	65,000 gas × 30	1,950,000 gas
Batched weekly	120,000 gas × 4	480,000 gas
Savings	75% reduction in gas costs	

[4]Empirical gas measurements were conducted using Ethereum mainnet test contracts for both naive decay and optimized "lazy decay" storage logic. The 17,000 gas savings is calculated as the difference in gas usage between recalculating and updating all balances on each block versus the optimized approach, which applies decay only on interaction. See full benchmarking code and methodology at `https://autophage.xyz/gas-optimization`.

10 Implementation Architecture

10.1 Core Smart Contracts

The protocol consists of four primary contracts with specific responsibilities [5]:

1. **AutophageToken**: Multi-species token with lazy decay evaluation

```
function balanceOf(address user, uint8 species) returns (uint256) {
    uint256 timeSince = block.timestamp - lastUpdate[user][species];
    uint256 decayFactor = (PRECISION - decayRate[species]) ** timeSince;
    return balance[user][species] * decayFactor / (PRECISION ** timeSince);
}
```

2. **ReservoirContract**: Dual-chamber treasury management

```
function processHealthcareClaim(Claim memory claim) {
    require(usdcBalance >= claim.amount, "Insufficient reserves");
    uint256 priority = calculatePriority(claim);
    priorityQueue.insert(claim, priority);
    processPriorityQueue();
}
```

3. **VerificationEngine**: zkVM proof processing

```
function verifyAndMint(Proof memory proof, uint8 species) {
    require(zkVerifier.verify(proof), "Invalid proof");
    uint256 amount = calculateReward(proof, species);
    tokenContract.mint(msg.sender, species, amount);
}
```

4. **GovernanceContract**: Experiment management

```
function evaluateProposal(uint256 proposalId) {
    Proposal memory p = proposals[proposalId];
    (uint256 improvement, uint256 pValue) = calculateResults(p);
    if (improvement >= MIN_IMPROVEMENT && pValue < ALPHA) {
        implementProposal(p);
        returnStakeWithBonus(p.proposer);
    }
}
```

[5] Each of the prospective smart contracts is viewable at https://autophage.xyz/smart-contracts. These contracts are experimental and so are intended solely for demonstration purposes.

11 Limitations and Future Work

11.1 Technical Limitations

Several constraints affect current implementation. Most notably, proof-generation overhead remains a significant challenge because, on mobile devices, modern zero-knowledge systems such as Groth16, Aurora, and Zexe [13, 4, 7] can take tens of seconds to generate a proof (and sometimes over a minute for complex circuits), while more optimized toolchains and smaller circuits may complete in 1–2 seconds [26]. This performance bottleneck limits user experience and complicates real-time verification.

Additionally, cross-chain fragmentation introduces complexity, as each blockchain environment demands a separate deployment and maintenance cycle, hindering seamless interoperability across ecosystems. Regulatory uncertainty further complicates matters; health token classification and compliance requirements vary by jurisdiction, making global rollout an ongoing challenge.

Beyond technical and legal constraints, behavioral inertia is perhaps the most stubborn evidenced by prior experiments with demurrage currencies consistently revealing user resistance to the very idea of "disappearing money" [11, 10]. As a result, there is a clear need for careful behavioral design and user education in any system based on token decay.

Example 11.1: Chronic condition adaptation:

User Type	Rhythm Decay	Special Adjustments
Standard user	5% daily	None
Mobility-limited	2.5% daily	Adjusted activity thresholds
Mental health focus	Standard	Healing tokens weighted 2x
Personalized	Variable	Based on verified medical needs

12 Conclusion

The Autophage Protocol demonstrates that economic systems can theoretically implement biological principles to create more equitable and health-promoting outcomes. By introducing mandatory token decay calibrated to health activity persistence, the protocol creates an economy where value must flow to exist, preventing the pathological accumulation that characterizes traditional monetary systems.

The mathematical framework suggests several promising properties. First, wealth distribution would likely converge to Gini coefficients [12] between 0.08 and 0.11 based on Monte Carlo simulations [1], compared to 0.82 for fiat currencies and 0.88 for Bitcoin.[6] This would occur through fundamental mechanics rather than redistribution or taxation. Second, the endogenous pricing model ties value directly to health effort, making speculation unprofitable while rewarding genuine wellness activities. Third, the privacy architecture enables verification without surveillance, solving a decades-old tension in public health monitoring.

The theoretical model indicates the protocol could achieve break-even at approximately 17,000 users with 91.7% contribution margins. The dual-chamber Reservoir design should maintain healthcare settlement guarantees even under extreme stress scenarios. The empirical governance system would enable continuous optimization based on statistically significant health improvements.

[6] Under adversarial conditions (23% of users acting adversarially), Gini remains capped below 0.55; see Appendix H for simulation details.

Perhaps most significantly, the protocol exists as a complete alternative to permanent-value economics. Where Bitcoin [24] provides digital gold and Ethereum [8] enables programmable contracts, the Autophage Protocol introduces digital metabolism. These three primitives, geological permanence, computational flexibility, and biological persistence, together could form a complete foundation for human-centric digital economies.

13 Works Consulted

References

[1] 0x42 Research. Gini coefficient simulation script. GitHub, 2025. https://autophage.xyz/gini-simulation.

[2] W.C. Allee. Animal aggregations: A study in general sociology. *University of Chicago Press*, 1931.

[3] Ian J. Amanna, Nicholas E. Carlson, and Mark K. Slifka. Duration of humoral immunity to common viral and vaccine antigens. *New England Journal of Medicine*, 357(19):1903–1915, 2007. Seminal study on long-term antibody persistence in humans. https://pubmed.ncbi.nlm.nih.gov/17989383/.

[4] Eli Ben-Sasson, Alessandro Chiesa, et al. Aurora: Transparent succinct arguments for r1cs. In *Annual International Conference on the Theory and Applications of Cryptographic Techniques*, pages 103–128. Springer, 2019. Whitepaper. https://eprint.iacr.org/2018/828.pdf.

[5] Carl Bergmann. Über die verhältnisse der wärmeökonomie der thiere zu ihrer grösse. *Göttinger Studien*, 3:595–708, 1847.

[6] Robert Blotevogel, Eslem Imamoglu, Kenji Moriyama, and Babacar Sarr. Income inequality measures and economic growth channels. *Journal of Macroeconomics*, 72:103413, 2022. https://www.sciencedirect.com/science/article/pii/S0164070422000167.

[7] Wu Bowe, Ariel Gabizon, et al. Zexe: Enabling decentralized private computation. In *Advances in Cryptology–EUROCRYPT 2020*, pages 967–1004. Springer, 2020. Whitepaper. https://eprint.iacr.org/2018/962.pdf.

[8] Vitalik Buterin. A next-generation smart contract and decentralized application platform. In *Ethereum White Paper*, 2014. https://ethereum.org/en/whitepaper/.

[9] Richard Dawkins. *The Selfish Gene*. Oxford University Press, 1976.

[10] Mark Ferguson and Freicoin Developers. Freicoin (demurrage-based cryptocurrency), 2013. Project homepage and overview: https://freico.in/about/; no reliable technical whitepaper available. For community description, see https://wiki.p2pfoundation.net/Freicoin.

[11] Silvio Gesell. *The Natural Economic Order*. Peter Owen Ltd., 1958. Full English text: Silvio Gesell Foundation. Available at https://www.silvio-gesell.de/the-natural-economic-order.html.

[12] Corrado Gini. Measurement of inequality of incomes. *The Economic Journal*, 31(121):124–126, 1921.

[13] Jens Groth. On the size of pairing-based non-interactive arguments. *Annual International Conference on the Theory and Applications of Cryptographic Techniques*, pages 305–326, 2016. https://link.springer.com/chapter/10.1007/978-3-662-49896-5_11.

[14] Austin Harshberger. Privacy-preserving health verification system with incentive mechanism for regular testing, 2025. https://0x42r.io/patents/1.pdf.

[15] Max Kleiber. Body size and metabolism. *Hilgardia*, 6(11):315–353, 1932.

[16] Bryan Kolb and Robbin Gibb. Neuroplasticity and behavior: current research and future directions. *International Review of Neurobiology*, 100:235–254, 2011. Comprehensive review of neuroplasticity timescales. https://pmc.ncbi.nlm.nih.gov/articles/PMC10425702/.

[17] Find Satoshi Lab. Step'n: Move-to-earn on web3, 2022. Whitepaper. https://whitepaper.stepn.com/.

[18] Simon A. Levin. Optimal foraging theory: A critical review. *Annual Review of Ecology and Systematics*, 7:141–154, 1976.

[19] Justus Liebig. Organic chemistry in its application to agriculture and physiology. *Journal of the Chemical Society*, 1840. https://www.loc.gov/item/12009827/.

[20] R.H. MacArthur and E.O. Wilson. The theory of the niche. *Population Biology*, 1:161–170, 1967.

[21] Timothy C. May. The crypto anarchist manifesto. *Extropy*, 1(2), 1997. https://www.activism.net/cypherpunk/crypto-anarchy.html.

[22] Branko Milanovic. Global inequality of opportunity: How much of our income is determined by where we live? *The Review of Economics and Statistics*, 97(2):452–460, 2015. https://direct.mit.edu/rest/article-abstract/97/2/452/58223/Global-Inequality-of-Opportunity-How-Much-of-Our?redirectedFrom=fulltext.

[23] I. Mujika and S. Padilla. Detraining: Loss of training-induced physiological and performance adaptations. part i: Short term insufficient training stimulus. *Sports Medicine*, 30(2):79–87, 2000. https://pubmed.ncbi.nlm.nih.gov/10966148/.

[24] Satoshi Nakamoto. Bitcoin: A peer-to-peer electronic cash system, 2008. https://bitcoin.org/bitcoin.pdf.

[25] Elinor Ostrom. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press, 1990.

[26] vacp2p. zksnark proving benchmarks on mobile devices (issue #7). https://github.com/vacp2p/research/issues/7, 2021. Accessed: 2025-07-13.

[27] John von Neumann. First draft of a report on the edvac, 1945. https://people.csail.mit.edu/brooks/idocs/VonNeumann_EDVAC.pdf.

14 Appendix

A Complete Feature Set

Table 4: Comprehensive Protocol Feature List

Feature	**Description**
Proof of Temporal Persistence	Core mechanism requiring continuous health activity to maintain token value through mandatory exponential decay
Four Token Species	Rhythm (5% daily), Healing (0.75%), Foundation (0.1%), Catalyst (2-10% dynamic) with decay rates matching activity persistence
Metabolic Pricing Model	Value emerges from measurable energy costs of health activities rather than market speculation
Dual-Chamber Reservoir	Separate token and USDC chambers ensure healthcare liquidity while managing community redistribution
Zero-Knowledge Privacy	Complete cryptographic separation of identity from health data using 768-bit entropy ProfileIDs
Genetic Adaptation System	Burn Foundation tokens to evolve up to 10 permanent earning traits creating personalized health profiles
Kleiber's Law Scaling	Network efficiency increases with $N^{0.25}$ providing benefits to all users as ecosystem grows
Liebig's Law Implementation	Automatic identification of system bottlenecks with 2x reward multipliers for constrained activities
Allee Effect Protection	Enhanced support multipliers (up to 2x) for networks below 1,000 users preventing death spirals
Circadian Rhythm Rewards	Time-of-day multipliers following natural biology with 30% peak bonus at optimal times
Empirical Governance	All protocol changes require on-chain A/B tests demonstrating 5%+ improvement with p ¡ 0.05
Privacy Marketplace Tiers	Anonymous, ProfileID, Genetic, and Full disclosure levels with 0-500% price premiums
Wellness Vaults	Time-locked token storage with reduced decay rates for healthcare saving (30-365 day terms)
Progressive Wealth Decay	Accelerated decay rates for large balances preventing extreme accumulation
Achievement Multipliers	Permanent bonuses for reaching health milestones (marathons, sobriety anniversaries, etc.)

Feature	Description
Synergy Bonuses	10-25% rewards for engaging multiple health domains daily promoting holistic wellness
Dynamic Energy Gradients	Counter-cyclical reward adjustments maintaining system sustainability during activity fluctuations
Healthcare Priority Queue	Medical settlements receive absolute priority with urgency-based processing
Community Catalyst Pools	Groups can purchase temporary ecosystem-wide activity boosts benefiting all participants
App Stake Requirements	Verification apps stake 10,000+ USDC with progressive slashing for false attestations
Seasonal Multipliers	Natural activity patterns reflected in rewards (e.g., 2.5x January for New Year motivation)
Statistical Fraud Detection	Anomaly detection prevents impossible activity claims using behavioral pattern analysis
Enterprise Verification API	Bulk wellness verification for corporate programs at $40/employee/year
Insurance Integration	Real-time premium adjustments based on verified healthy behaviors
Time-Decayed Cash Access	Formula $A(t) = 0.3+0.7\times0.8^t$ preserves healthcare utility while discouraging hoarding
Contribution Scoring	Lifetime ecosystem value determines governance weight rather than current token holdings
Feature Natural Selection	Unused features sunset automatically after 180 days below 1% utilization
Parameter Evolution	System constants adjust based on empirical health outcomes from experiments
Cross-Activity Bonuses	Complementary activities earn compound rewards (e.g., exercise + therapy = 1.5x multiplier)
Recovery Support System	Enhanced rewards and reduced decay during verified health setbacks
Geographic Equity Module	Automatic support for underserved regions through dynamic multiplier adjustments
Research Data Feeds	Anonymized aggregate health behavior data available for public health research
Liquidity Provision Rewards	Catalyst tokens for providing marketplace liquidity and facilitating trades
Multi-Signature Security	Critical protocol functions require 7-of-9 guardian signatures preventing single points of failure

B Glossary of Terms

Autophage
Self-consuming; in the protocol context, value that must decay to create circulation and prevent accumulation.

Catalyst Tokens
Fourth token species with dynamic 2–10% decay maintaining 25% ecosystem balance through automatic adjustment. Catalyst tokens are earned through marketplace participation and protocol activity, used for staking, governance proposals, and price discovery tied to metabolic pricing. They cannot be vaulted or saved.

Circadian Multiplier
Time-of-day reward adjustment following natural biological rhythms, maximizing at 6 AM (1.3x) and minimizing at 6 PM (0.7x).

Contribution Score
Governance weight calculated from lifetime Reservoir contributions, reputation, and participation rather than current holdings.

Decay Rate (δ)
Daily percentage of token value lost, ranging from 0.1% (Foundation) to 5% (Rhythm) based on activity persistence.

Dual-Chamber Reservoir
Community treasury architecture separating decaying tokens from USDC reserves to ensure healthcare liquidity.

Endogenous Price
Value determined by internal health activity energy costs rather than external market speculation.

Foundation Tokens
Slowest-decaying species (0.1% daily) earned through preventive care and long-term health investments.

Genetic Adaptation
System allowing users to burn Foundation tokens for permanent earning traits, creating specialized economic profiles.

Gini Coefficient
A statistical measure of how wealth is distributed in a system. Zero means everyone holds the same amount, while one means a single participant holds everything. In this protocol, a lower Gini coefficient signals that value is circulating widely. Most national currencies and cryptocurrencies show Gini values above 0.80.

Half-Life
Time required for token balance to reduce by 50% without renewal; 13.51 days for Rhythm, 92.42 for Healing, 693 for Foundation.

Healing Tokens
Token species with 0.75% daily decay earned through therapy, recovery, and mental health activities.

Kleiber's Law
: Biological scaling law implemented as $\eta(N) = 1 + 0.3(N/1000)^{0.25}$, increasing efficiency with network size.

Liebig's Law
: Principle that system health equals its weakest component, triggering automatic reward rebalancing.

Metabolic Pricing
: Price discovery based on actual energy expenditure (time, calories, opportunity cost) of health activities.

ProfileID
: Cryptographic identifier with 768-bit entropy separating user identity from health activity data.

Proof of Temporal Persistence (PoTP)
: Core protocol mechanism requiring continuous activity to maintain value, preventing passive accumulation.

Rhythm Tokens
: Fastest-decaying species (5% daily) earned through exercise, medication adherence, and daily health habits.

Soft Cap
: Balance threshold triggering accelerated decay to prevent excessive accumulation while allowing reasonable savings.

USDC
: Dollar-pegged stablecoin issued by Circle and Coinbase. Used as a programmatic, fully-backed USD equivalent for on-chain settlements.

Wellness Vault
: Time-locked token storage with reduced decay rates enabling targeted healthcare saving.

Zero-Knowledge Proof
: Cryptographic method verifying health activities without revealing personal data, maintaining privacy.

zkVM Orchestration
: Application layer managing proof generation across heterogeneous health apps while preserving privacy.

C Selected Use Case Examples

The following use cases are hypothetical. Each user journey is designed to show how the protocol works in practice. No story describes a real person or actual event. These are demonstrations of what is possible with the Autophage Protocol.

C.1 Marathon Training: Sarah's Journey

Sarah, a 29-year-old software engineer, uses the protocol to fund her gender-affirming surgery while training for marathons. Her daily routine generates multiple token streams:

Morning runs earn 50–75 Rhythm tokens depending on distance and intensity. Her 30-day streak multiplier has grown to 2.48x, while her "Early Bird" genetic trait adds 15% for pre-7 AM activities. Weekly therapy sessions generate 80 Healing tokens each, with her "Mental Resilience" trait providing an additional 12% bonus.

Her Chicago Marathon completion created particularly valuable proof:

Reward Component	**Value**	**Tokens**
Base marathon reward	Standard	200 Foundation
Sub-4:30 time bonus	1.5x multiplier	Applied
Perfect weather penalty	0.9x	Applied
Total generation	$200 \times 1.5 \times 0.9$	**270 Foundation**

The zero-knowledge proof included timing chip data, GPS traces, heart rate patterns, and photographic evidence, compressed into a verifiable statement: "Female 25–34 completed major marathon in 4:27:33." She listed this anonymously for $300, receiving $264 after fees.

Current progress toward $4,000 surgery goal:

Income Source	**Amount**
Token value	$2,847
Proof sales	$1,584
Monthly average	$132
Months to goal	3.5

Sarah's public ProfileID has attracted a following among trans athletes. While her gender identity remains private, her consistent performance inspires others facing similar journeys.

C.2 Recovery Economics: Marcus's Story

Marcus discovered the protocol on day 387 of sobriety. While physical fitness remained challenging, his daily recovery meetings became an economic foundation.
Each meeting generates 40 Healing tokens, with milestones providing substantial bonuses:

Milestone	Token Bonus
30 days continuous	300 tokens
90 days	900 tokens
1 year	3,000 tokens
18 months	4,500 tokens

His genetic evolution focused on recovery optimization:

Trait	Benefit	Bonus	Cost
Recovery Resilience	General recovery bonus	15%	1,000 Foundation
Social Connection	Group activity bonus	12%	2,500 Foundation
Consistency Rewards	Streak bonus	10%	5,000 Foundation
Healing Focus	Healing token bonus	20%	10,000 Foundation

Combined multipliers mean his daily meetings now generate 72 tokens instead of the base 40. His 12,000 Healing token balance represents $8,040 in value, providing financial security that supports sustained recovery.

Marcus monetizes his journey selectively. Anonymous daily proofs sell for $2-3 to researchers studying recovery patterns. His one-year sobriety proof sold for $100. Monthly proof sales generate $180 supplemental income, funding gym membership and therapy co-pays.

The economic visibility of recovery has transformed his self-perception. "My sobriety has measurable value," he tells newcomers. "Every day clean creates wealth for myself and data that helps others."

C.3 Creator Economy: Luna's Empire

Luna leverages the protocol to differentiate her 850K subscriber OnlyFans empire. Unlike competitors relying on photo editing and claims, she provides cryptographically verified fitness achievements. Her daily routine becomes multi-stream content:
Morning workout routine:

Component	Multiplier	Value
Base reward	-	50 Rhythm tokens
6 AM circadian bonus	1.3x	Applied
Livestream multiplier	1.5x	200+ viewers
Performance Aesthetics trait	15%	Applied
Camera Ready trait	12%	Applied
Total generation	Combined	**115 Rhythm tokens**

Every activity generates both tokens and content.
Post-workout biometrics create Foundation tokens while providing transparency her audience craves. Meal prep earns tokens while teaching nutrition. Even rest days generate Healing tokens through documented recovery practices.

Her proof monetization strategy:

Proof Type	Individual Price	Bundle/Package
Daily workout	$5	$100/month
Transformation	-	$200 (90-day)
Personal records	$50-500	Varies by achievement
Genetic trait revelation	$1,000	One-time

With 17,000 proof subscribers paying $200/month average, Luna generates $3.4M monthly from verification alone. The protocol's 12% marketplace fees seem minimal compared to the trust premium her verification commands.

D Plain Language Summary

Traditional money persists indefinitely. A dollar earned decades ago maintains its value without effort. This permanence creates economies where wealth concentrates among those who already possess it, while those who need resources most must continuously labor for finite rewards. The Autophage Protocol introduces a fundamental alternative through money that decays.

The protocol creates four species of digital tokens, each calibrated to match the persistence of different health activities. Exercise tokens decay at five percent daily, reflecting how quickly cardiovascular fitness deteriorates without maintenance. Therapy tokens decay at three-quarters of one percent daily, mirroring the gradual erosion of mental health progress. Preventive care tokens decay at one-tenth of one percent daily, representing the long-term nature of vaccinations and screenings. A fourth species, Catalyst tokens, maintains ecosystem balance through dynamic decay rates.

Every token must be earned through verified health activity. Running generates Rhythm tokens. Therapy sessions produce Healing tokens. Annual checkups create Foundation tokens. The system rewards consistency through multipliers where morning workouts earn circadian bonuses, group activities multiply rewards, and sustained streaks compound earnings. Users who exercise daily maintain steady balances, while inactive users watch their balances decrease.

Decayed tokens flow to The Reservoir, a dual-chamber treasury at the protocol's heart. One chamber collects expired tokens and redistributes them as rewards for new activities. The other maintains stablecoin reserves to settle real healthcare expenses. This architecture ensures that individual decay creates collective wealth, funding community health infrastructure through the natural expiration of unused value.

Privacy remains absolute through cryptographic separation. The system verifies that you exercised without revealing when, where, or how. Users control their disclosure level, from complete anonymity to selective revelation of patterns that command premium prices in health data markets. Researchers purchase aggregated proofs to study behavior patterns. Insurers adjust premiums based on verified activities. Individuals monetize their consistency without sacrificing privacy.

The protocol implements biological scaling laws throughout. Network effects follow Kleiber's Law, increasing efficiency as the ecosystem grows. Bottlenecks trigger automatic rebalancing through Liebig's Law. Small communities receive enhanced support through Allee Effect multipliers. Every mechanism derives from observed biological systems rather than economic theory.

Users adapt their economic metabolism through genetic traits, using Foundation tokens to evolve permanent earning multipliers. Wellness vaults enable targeted saving by reducing decay rates for locked tokens. Progressive decay acceleration prevents extreme accumulation. Empirical governance requires all changes to demonstrate measurable health improvements through on-chain experiments.

The result transforms economics from a system of accumulation to one of circulation. Wealth flows or disappears. Health activities generate immediate value. Privacy and transparency coexist through mathematics. The Autophage Protocol experiment poses a fundamental question: can an economy modeled on living systems create more equitable and sustainable outcomes than one modeled on geological permanence?

E Understanding the Math for Everyone

This appendix explains the paper's formal notation so that any motivated reader can understand what is being described. Mathematics serves two purposes in this protocol. It makes rules unambiguous and repeatable, and it allows anyone to verify or critique the system's logic without relying on trust or marketing claims.

Mathematical Symbols in Context

Table 5: Common Mathematical Symbols in the Autophage Protocol

Symbol	Meaning	Example Use
δ	Decay rate, the fraction of value lost per period	$\delta = 0.05$ means 5% daily decay
λ	Growth or scaling rate (context-dependent)	λ may set user onboarding pace
$\sum$	Summation, sum all values in a range	$\sum_{i=1}^{n} x_i$ means add x_1 to x_n
γ	Sensitivity or acceleration parameter	γ increases effect in adaptive decay
i, j, u	Indices for species, activities, or users	$V_i^{(u)}$ is species i for user u
(t)	Value at time t	$G_i^{(u)}(t)$ means reward at time t
$\lvert x \rvert$	Absolute value, distance from zero	$\lvert -3 \rvert = 3$
$^{(u)}$	Superscript shows the user u	$V^{(u)}$ is value for user u

Why These Symbols? A Brief History and Rationale

Many of the mathematical symbols used here have a long history, appearing in physics, biology, and economics:

Table 6: Historical and Disciplinary Context of Core Mathematical Symbols

Symbol	Origins & Common Uses	Why Used Here
δ	Greek letter delta. Used for small changes or decay (calculus, physics, biology).	Represents decay rates for token value, mirroring biological loss or depreciation.
λ	Greek letter lambda. Denotes growth rates, eigenvalues (math, ecology, economics).	Captures system growth, arrival rates, or user inflow; signals scaling or tempo.
$\sum$	Uppercase sigma. Ancient Greek, adopted in 18th-century math. Standard for summing sequences (statistics, physics, economics).	Indicates summing over activities, users, or token classes; fundamental to reward calculations.
γ	Greek letter gamma. Used for rates of change, sensitivity, and scaling (physics, econometrics).	Adjusts the strength or "sharpness" of protocol effects (such as how quickly penalties accelerate).

How to Read the Equations Aloud

Here are examples of how to say these formulas out loud, and how to "translate" notation to spoken language:

Example 1: Token Balance Evolution

$$V_i^{(u)}(t+1) = V_i^{(u)}(t)(1-\delta_i) + G_i^{(u)}(t)$$

Read aloud: "V sub i, superscript u, at time t plus one, equals V sub i, superscript u, at time t, times one minus delta sub i, plus G sub i, superscript u, at time t." In plain English, this means: "The balance for user u, token species i, tomorrow, equals today's balance after decay, plus the new tokens earned."

Example 2: Adaptive Catalyst Decay

$$\delta_{catalyst}(t) = \delta_{base} \times \left(1 + \beta \times \left|\frac{V_{catalyst}(t)}{\sum_{i \in S} V_i(t)} - \rho_{target}\right|^{\gamma}\right)$$

Read aloud: "Delta sub catalyst at time t equals delta base times the quantity one plus beta times the absolute value of the ratio of V catalyst at t over the sum from i in S of V sub i at t, minus rho target, all raised to the power gamma."

For clarity:

- "Sub" means the subscript (the variable after the underscore).
- "Superscript" (or "to the power") means the small number or letter above the main symbol.
- $\sum_{i=1}^{n} x_i$ is read "the sum from i equals one to n of x sub i."
- Greek letters are read by name: "delta," "lambda," "gamma," "rho."

No mathematical symbol in this paper is used for gatekeeping. The explicit notation is necessary for precision and trust. Each equation can be seen as a technical contract between the protocol and its users. If anything is unclear, these tables provide a reference for decoding the symbols, and every formula can be read aloud, checked in simulation, or translated into code. In short, the math is here so anyone can follow the logic, test the claims, and keep the system honest.

F Note from the Author

Biomimetics, if it means anything, is enforcement rather than metaphor.

In Autophage, decay is structural. Value dies if it does not circulate. Most systems treat nature as garnish; here, mortality is code. Accumulation outside of health savings is a liability.

The status quo rewards stasis and calls it success. In health and in money, what survives is what moves. Everything else is just afterlife accounting.

–

The Autophage Protocol and Proof of Temporal Persistence remain an experiment in economic design, one I hope to implement when time and resources allow. The mathematics have been carefully developed and the simulations run thousands of times, but the true test lies in whether individuals and communities will choose renewal, flow, and life over accumulation, comfort, and stasis.

With this paper, the theoretical framework is complete; only practical implementation awaits. My hope is that, in creating value which must move to exist, we might discover economics that prioritize continual renewal of value, mirroring living systems and benefiting all instead of the few.

The mathematics of decay could become the foundation for sustainable abundance, but only real-world deployment will reveal if theory translates to practice.

G Acknowledgments

This work stands on the shoulders of giants.

Deep gratitude to my family and friends who provided both emotional support and critical feedback through countless iterations. Your patience with my obsession over decay rates and biological metaphors exemplifies the human connections that make any economic system worthwhile.

The protocol builds upon decades of groundbreaking work in cryptography and distributed systems. I acknowledge the cypherpunks [21] who first envisioned private digital cash when such ideas seemed impossible. The zero-knowledge research community [13] transformed privacy from policy to mathematics, making health verification without surveillance achievable. Bitcoin [24] demonstrated programmable scarcity. Ethereum [8] generalized blockchain computation. The broader ecosystem continues advancing human freedom through code.

I learned a lot from researchers and writers like Dawkins [9], Ostrom [25], von Neumann [27], and from reading far too many papers instead of sleeping. They didn't endorse this work, but their ideas made it possible to approach health and economics differently.

And to OpenAI and Anthropic for their AI language models, which served as tireless intellectual companions, helping bridge evolutionary biology, cryptographic theory, and economic modeling while enabling rigorous mathematical formalization and technical validation.

Thank you all.

H Adversarial Stress Test

Methodology

To test protocol resilience, a Monte Carlo simulation was run with 10,000 users over 365 days. Twenty-three percent of users were assigned adversarial behaviors intended to maximize wealth concentration and increase the Gini coefficient. Eight attack strategies were implemented, including sybil swarm formation, passive hoarding, coordinated collusion, periodic burst activity, churn-based exploitation, whale concentration, front-run transfers, and composite adaptive attacks. All simulation parameters (decay, activity rate, whale decay thresholds) matched those in the main experiments.

Results

Despite sustained adversarial activity, the protocol demonstrated significant resistance to inequality amplification.

Table 7: Summary of Adversarial Stress Test Outcomes

Condition	**Final Gini Coefficient**	**Interpretation**
Baseline (clean)	0.33	Equitable equilibrium
Adversarial (23%)	0.55	Moderate inequality, system robust
US Dollar	0.82	Pathological inequality
Bitcoin	0.88	Pathological inequality

The highest Gini observed at initialization was 0.63, reflecting initial distribution noise. At one year, the system stabilized at a Gini of 0.55 which is higher than baseline, but well below traditional currencies and cryptocurrencies.

Sybil swarms produced the wealthiest individual accounts, but failed to generate runaway inequality. All other attack vectors, including passive hoarding and collusive pooling, were limited by the protocol's decay mechanics and progressive whale decay.

Hoarding and inactivity consistently led to rapid value loss, demonstrating that "money must move" is a structural property.

Mechanisms of Robustness

Three protocol mechanisms proved decisive:

1. **Universal decay:** Exponential decay applies to all balances, regardless of strategy or identity.

2. **Progressive whale decay:** Accumulated balances experience accelerated decay, capping potential for dominance.

3. **Activity coupling:** Reward accrual remains inseparable from continuous participation; passive or cyclical exploit attempts are self-limiting.

Conclusion

Adversarial simulation confirms that no known strategy can meaningfully circumvent enforced decay and activity requirements. Even with coordinated attacks and sybil formations, the protocol maintained Gini coefficients below those observed in all major legacy and digital monetary systems. This outcome validates the protocol's core claim that value must circulate to persist, and attempts to evade circulation lead only to accelerated loss.

I On the Irreversibility of Health Value Conversion

Conversion between token species is not permitted within the Autophage Protocol.

Each token species, Rhythm, Healing, Foundation, and Catalyst, functions as a discrete record of a particular kind of health persistence. The protocol is intentionally designed to make these categories non-fungible because doing so serves as a structural assertion about how value should reflect real-world persistence.

Allowing conversion between tokens would erode the biological foundation of the protocol, making it possible to "farm" one domain of health for rewards in another. In practice, such a mechanism would create arbitrage opportunities, invite speculation, and undermine the protocol's core behavioral incentives. Metabolic activity is not inherently fungible; cardiovascular endurance cannot be traded for vaccine immunity, and emotional recovery cannot be converted into daily exercise.

Proof of Temporal Persistence is defined by the activity that generates each token. If a user wishes to hold more Foundation tokens, they must engage in preventive care; to increase Healing tokens, they must participate in therapy or recovery. The marketplace allows users to monetize verified actions or proofs, but does not flatten the specific metabolic history those proofs represent. Catalyst tokens serve as the protocol's primary "liquidity" vector for governance and marketplace functions, but are not a substitute for sustained health actions in any other domain.

This irreversibility anchors the protocol to the realities of biology, closing the door to speculative gamesmanship and ensuring that economic rewards remain tethered to real, verifiable health persistence.

Each token is a distinct receipt for a unique kind of effort and persistence.

If you want Foundation, you must do the work.

J AI Attestation

This paper was assisted by Claude 4 Opus and ChatGPT 4.1-5. These tools served a role similar to LaTeX for typesetting or computational systems for verification, enabling more rigorous expression and validation of ideas. All core concepts, insights, and creative decisions are original human work.[7]

[7]For detailed AI tool attribution and transparency, see the attest.ink verification URL. If this paper is being read non-digitally, use this link: https://attest.ink/verify/?id=2025-07-16-gdl42d

K Version History

Table 8: Protocol Evolution Timeline

Version	Date	Major Changes
v0.1	May 2025	Initial concept: health verification with privacy
v0.2	June 2025	Introduced decay mechanics and biological metaphors
v0.3	June 2025	Formalized Proof of Temporal Persistence
v0.4	June 2025	Multiple token species with variable decay
v0.5	June 2025	Complete shift to metabolic economics paradigm
v0.6	June 2025	Dual-chamber Reservoir architecture
v0.7	June 2025	Mathematical formalization for academic review
v0.8	June 2025	Precision alignment with implementation
v0.9	June 2025	Catalyst tokens and marketplace dynamics
v1.0	June 2025	Individual metabolic capacity model
v1.1	June 2025	Governance refinements and corrections
v1.2	July 2025	Adversarial stress testing; Gini remains < 0.55
v1.3	July 2025	Complete academic paper for arXiv