The $\mathcal{NRCSTK}$ Neuron: Survival-Driven Learning via Spectral Tuning Under Metabolic Competition

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1. Introduction

What would **AI/ML look like** *if it had to* **evolve within** *the physical and* **energetic limitations of real hardware**, *without access to cloud resources or labeled data?*

The **brain learns without labels**, all without a global orchestrator.

Canonical AI assumes centralized training signals.

Constraint	Canonical AI/ML	Hardware reality	Biological parallel
Local Autonomy	Global objective	Bandwidth constraint / Congestion	Neurons learn **locally** (bAP)
Template autonomy	Requires Labels / Targets	No labels on edge	No external template. Everything input-driven.
Clock autonomy	Scheduled steps. Backprop. (Forward/Backward)	Global training clock -> pipelining (Design is costly - OoO is hard)	Dynamics are **asynchronous**.

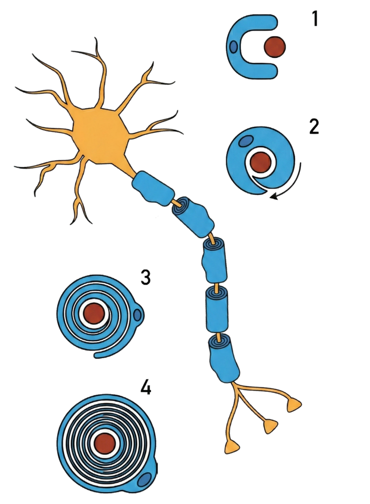
The ideal autonomous self-learning hardware

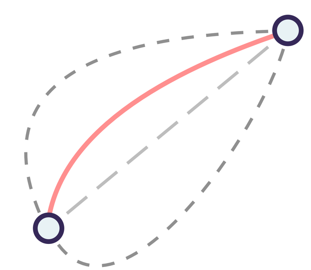
- **Local learning** (No global knowledge)
- **Target-free** (No explicit labels)
- **Asynchronous** (Local evolution)
- **Thermodyn. constrained** (Energy efficient)

2. Neurobiological inspiration

The **autopoietic** [1] *frame:* **each cell**/*compartment as an* **independent agent** *under* **metabolic pressure**. **Learning** *is an* **emergent property of survivability**.

- Metabolic constraints. Limited energy limits computation [2]
- Glial support and activity reward
  - Astrocytes couple synaptic activity to metabolism [3,4]
  - Oligodendrocytes (Myelinization investment) metabolically support and enable long-range communication [5].
  - Energy delivery is integrated with neural signaling and tracks computation [6].
- Dynamical neurons:
  - Brains self organize: Neural avalanches [7] and criticality are the fingerprints of complexity and emergence.
  - Oscillations and resonance: Rich firing patterns can emerge from low-dimensional continuous time dynamics [8, 9].





Normative framing:

- Least action principle. Conservation laws and symmetries in real-life commonly make dynamical systems follow the path of least action.

$$\delta S = \delta \int_t L\, dt = 0$$

3. The $\mathcal{NRCSTK}$ framework

Cost of existing - Mass as a proxy for commitment

- Neurons carry a metabolic mass m_k which has to be sustained with q_k
- Dynamical properties (ω_k, γ_k) are modulated by mass m_k
- More mass = more capability ⟶ **Learning as an allocation problem.**

A competitive metabolic market

- Global metabolic flux Q is split into per-branch shares $\pi_k \rightarrow q_k = \pi_k Q$
- Branches **compete for share**: useful branches grow; redundant starve.
- Signal entanglement as reward deservability ⟶ **100% local learning.**

Emergent learning (specialization + synchronization)

- Branch dynamics drive **spectral specialization**.
- Deflation encourages branches to tune to explained components ξ
- Competition produces **repulsion**
- **Synchronization emerges as stable point.**

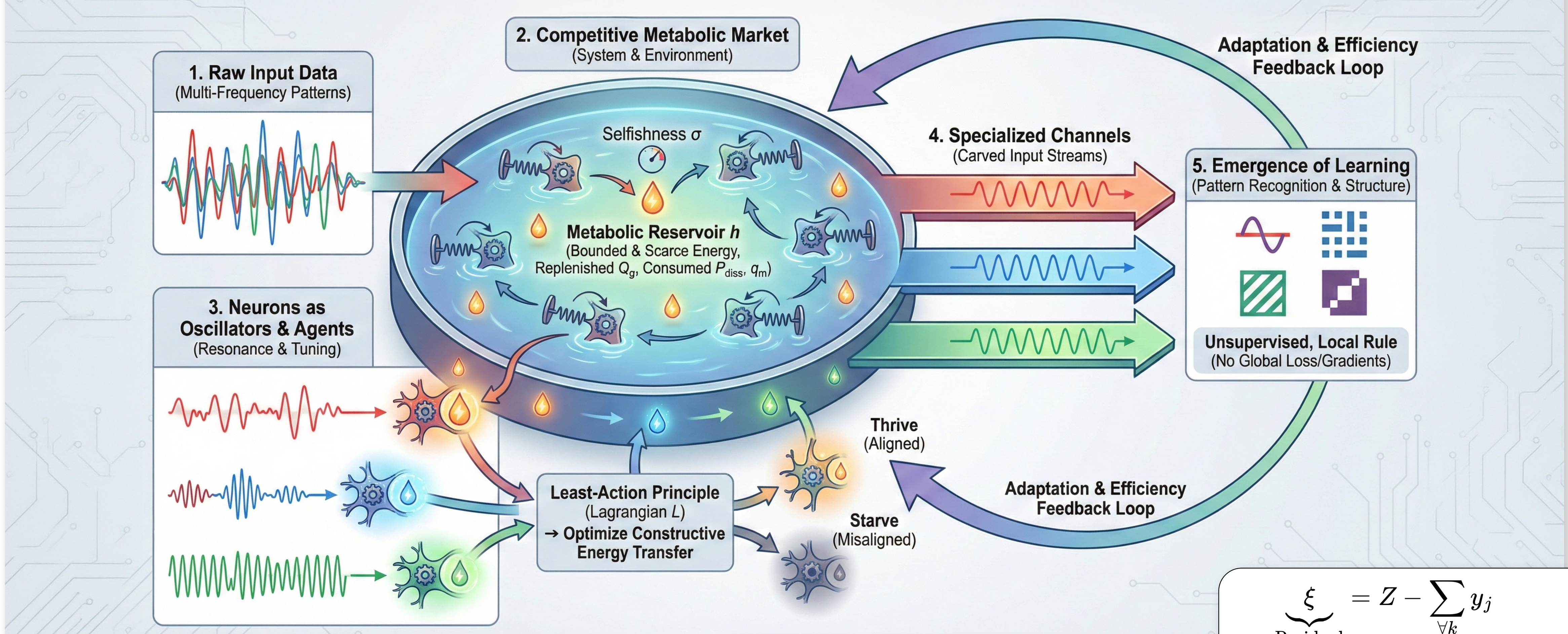
$$\begin{bmatrix} x_I \\ x_E \end{bmatrix} = m \begin{bmatrix} c_I & 0 \\ 0 & c_E \end{bmatrix} \begin{bmatrix} 1-\eta & \eta \\ \eta & 1-\eta \end{bmatrix} \begin{bmatrix} s \\ 1-s \end{bmatrix}$$

$$x_D = c_D\, m^{\delta}$$

$$x_I \ddot{\psi} + x_D \dot{\psi} + x_E \psi = \zeta$$

$$\dot{m} = \mu^{+} q - \mu^{-} m$$

$$\underbrace{\frac{\dot{\pi}_k}{\pi_k}}_{\text{reward share}} \propto \underbrace{(f_k - \bar{f})}_{\text{fitness advantage}} + \beta \sum_{j \neq k} \underbrace{\rho_{k,j}}_{\text{overlap}}\, g(\pi, f)$$



$$\ddot{\psi} + \underbrace{2\gamma(m)\dot{\psi}}_{\text{mass-dependent}} + \underbrace{\omega^2(s)\psi}_{\text{mass-independent}} = \underbrace{\frac{\zeta}{x_I}}_{\text{input}}$$

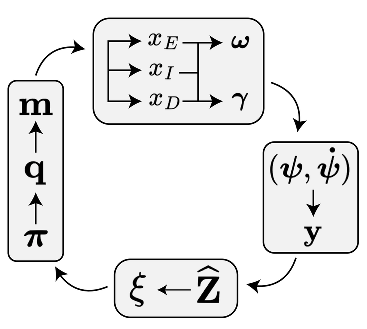
$$\dot{\omega} \propto \frac{\overbrace{\mathcal{T} - \mathcal{V}}^{\text{Lagrangian } \mathcal{L}}}{\underbrace{\mathcal{T} + \mathcal{V}}_{\text{Total energy } \mathcal{E}}} \qquad \mathcal{T} = \tfrac{1}{2} x_I |\dot{\psi}|^2 \quad \mathcal{V} = \tfrac{1}{2} x_E |\psi|^2$$

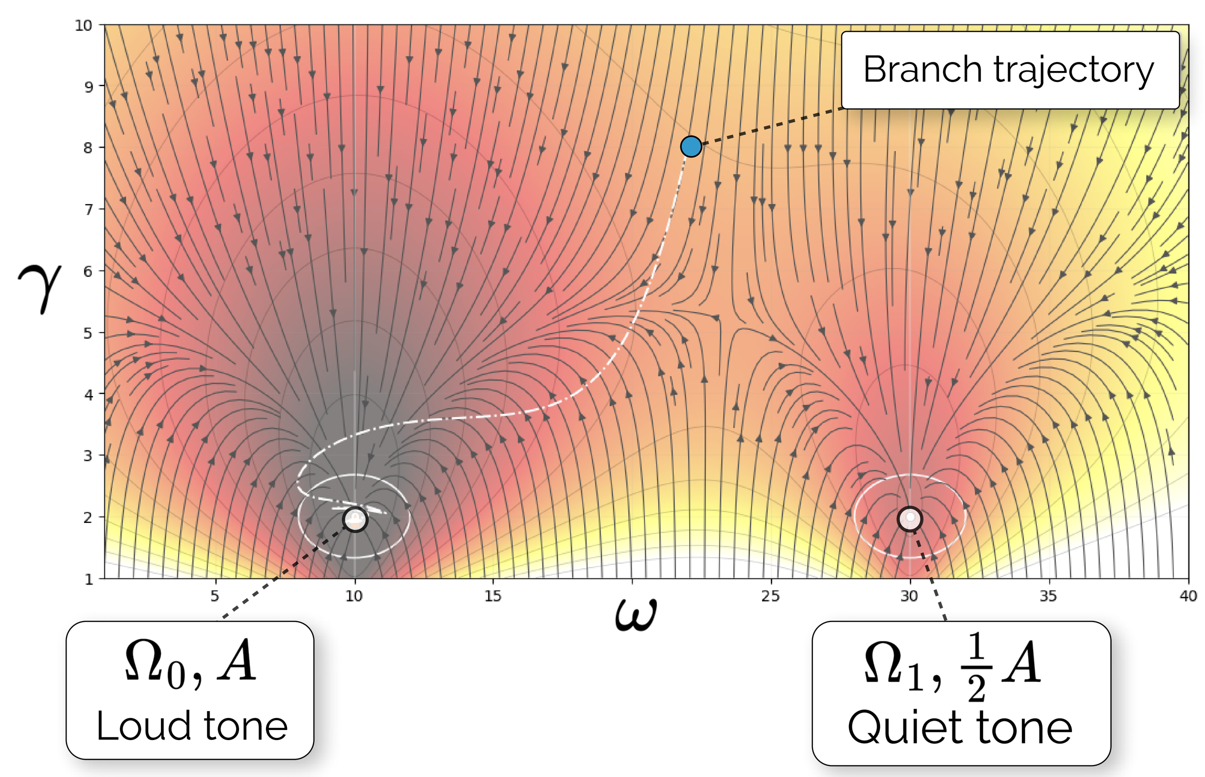
$$\underbrace{\xi}_{\text{Residual}} = Z - \sum_{\forall k} y_j$$

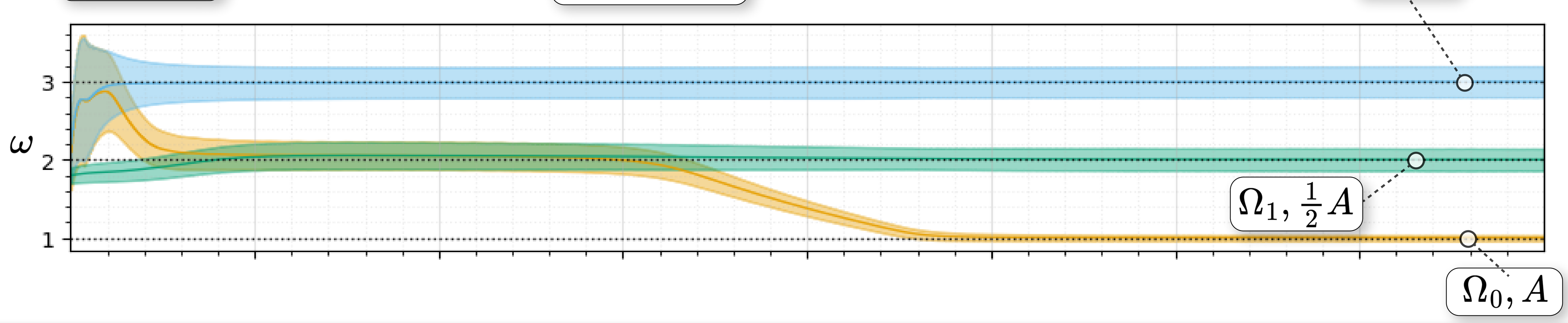
$$\underbrace{\zeta_k}_{\text{Branch input}} = \underbrace{Z}_{\text{Input}} - \underbrace{\sum_{j \neq k} \chi_{kj} y_j}_{\text{lat. inhibition}}$$

4. Spectral predation ecology and self organization

- **Residual/deflation**: Each branch focuses on a spectral band ζ_k
- Bigger branches **predate** smaller branches share q_k
- **Positive feedback** reinforces spectral decomposition.



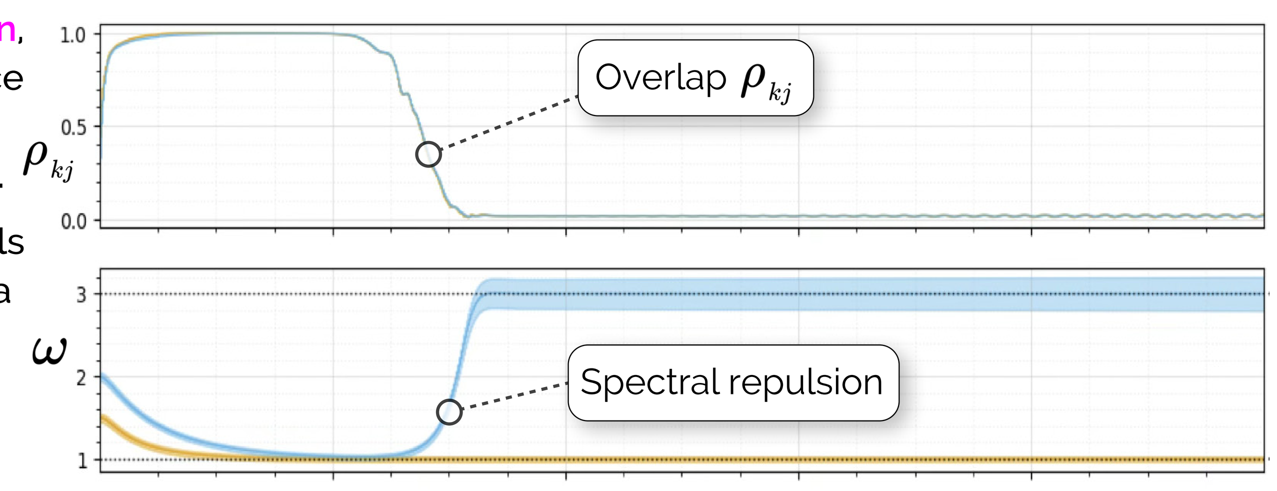


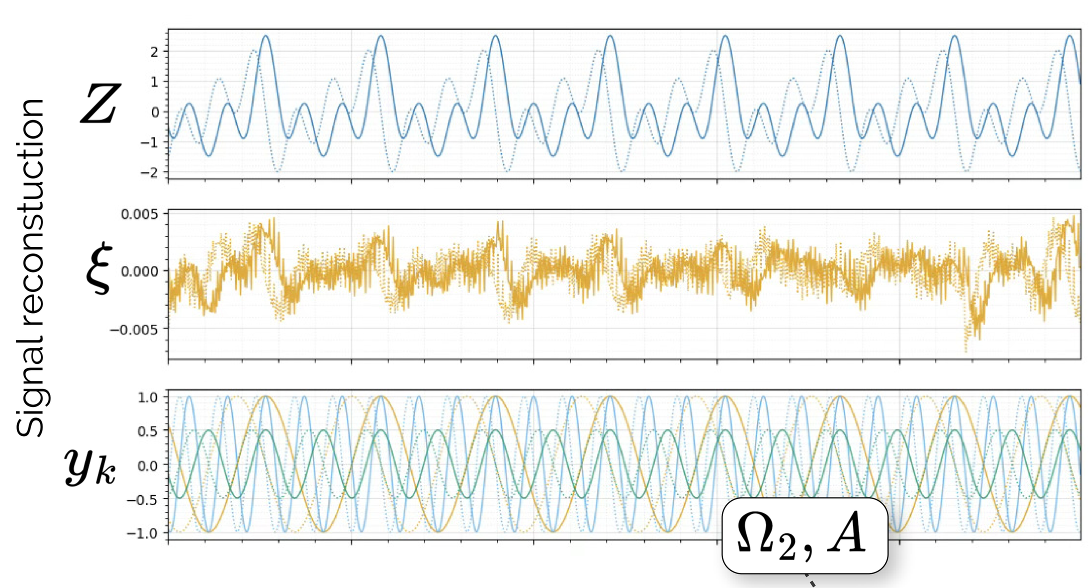


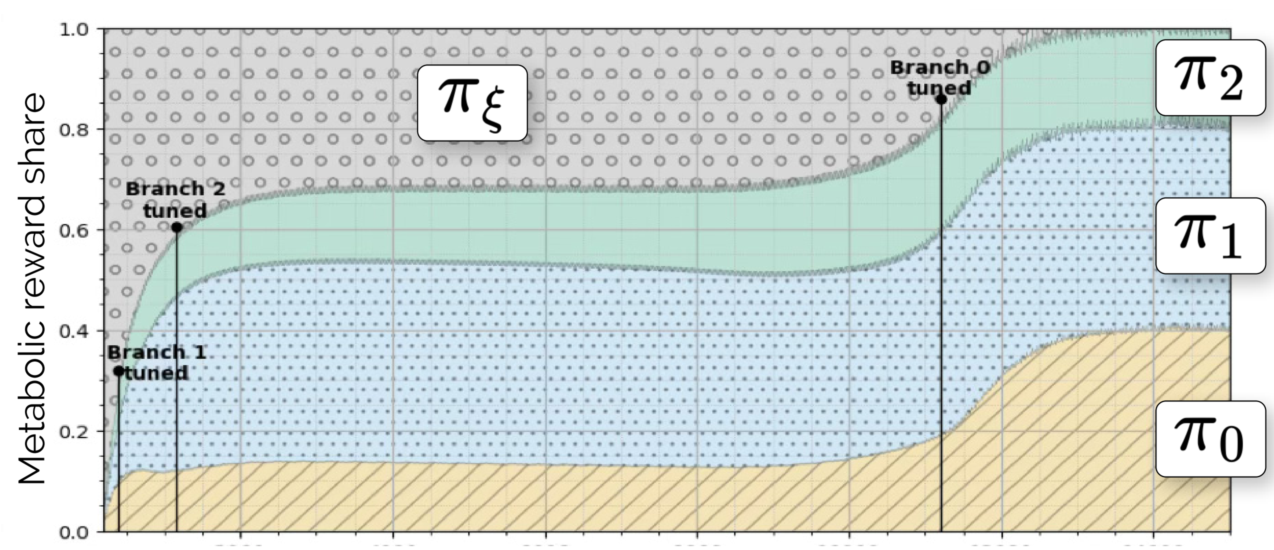
5. Results and Future work

- We presented the $\mathcal{NRCSTK}$ framework: a metabolism-driven, locally self-tuning ecosystem where competition over scarce resources makes spectral decomposition of inputs the optimal learning strategy. Synchronicity emerges as a result.
- **Under investigation**: map $\mathcal{NRCSTK}$ state variables and signals onto concrete electrical circuit components and prototype a minimal $\mathcal{NRCSTK}$ **neuron ASIC demonstrator**.

$\mathcal{NRCSTK}$ *puts us on a credible path toward one of the first* ***self-tuning, metabolically driven on-hardware learning.***







References and Acknowledgements

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