

● INAUGURAL WORKSHOP ON ACTIVE INFERENCE IN ITALY

The Metabolic Foundations of Economic Behavior

*An active inference account of the cost of cognition
and its consequences for economic theory*

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● OVERVIEW

One constraint, three theoretical responses

The argument rests on a single empirical premise: for a living nervous system, inference is metabolically costly. Three frameworks treat that premise differently.

NEOCLASSICAL ECONOMICS

Omits

Treats inference as costless and unbounded.

BEHAVIORAL ECONOMICS

Relabels

Reads the resulting economies as bias.

ACTIVE INFERENCE

Formalizes

Represents the cost explicitly, as precision.

- *How this constraint is treated is what distinguishes the three frameworks.*

I

The metabolic constraint and standard economics

We begin with the empirical premise and its consequences: inference is metabolically costly, a fact that neoclassical theory omits and that behavioral economics interprets as irrationality.

● THE METABOLIC CONSTRAINT

The energetic cost of cognition is dominated by signaling

20%

of the body's energy

2%

of its mass

About 70% of the gray matter's energy supports **signaling**, with synaptic transmission the largest single component. Because cost scales with activity, only a small fraction of neurons can be active at once; sparse, approximate computation reflects this energetic constraint.

Attwell & Laughlin 2001 · Howarth et al. 2012 · Lennie 2003

- *Signaling, not maintenance, is the principal cost, and the energy budget constrains it.*

● ENERGY BUDGET OF SIGNALING

Synaptic transmission dominates the energy budget

Most gray-matter ATP is spent on signaling. The modern budget, after correcting for the efficiency of mammalian action potentials, places the largest share on postsynaptic currents:



Of signaling energy (Howarth et al. 2012): postsynaptic currents 50% · action potentials 21% · resting potentials 20% · presynaptic & recycling 9%

Signaling is the majority of gray-matter ATP; housekeeping accounts for the remainder ($\approx 25\text{--}40\%$).

A single action potential with its synaptic consequences consumes on the order of 10^9 ATP molecules, and glucose use rises approximately linearly with firing rate. The budget sustains only about 1% of neurons active at once (Lennie), enforcing sparse codes, and aerobic glycolysis is elevated where synaptic plasticity and growth are greatest.

Attwell & Laughlin 2001 · Alle et al. 2009 · Howarth et al. 2012 · Lennie 2003 · Goyal et al. 2014

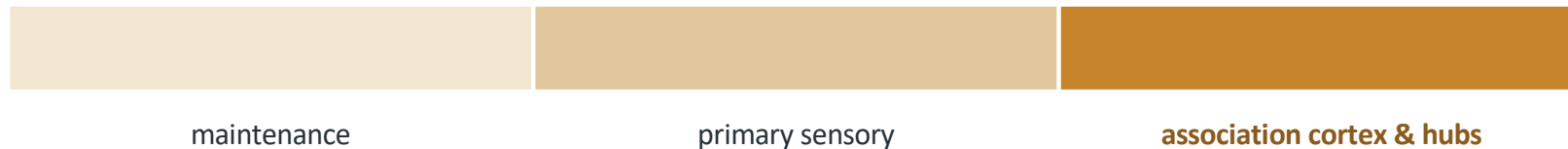
- *These quantitative results underlie the claim that inference is costly and must be economized.*

● REGIONAL METABOLIC COST

The highest costs fall on higher-order, integrative cortex

The connectome is organized to trade the wiring cost of long-range connections against integrative efficiency. The highest costs fall on the **connector hubs** and the networks for attention, working memory, and decision-making, which run hotter than sensory cortex even at rest and consume disproportionately more energy per unit of tissue.

metabolic cost per unit of computation →



Bullmore & Sporns 2012 · Vaishnavi et al. 2010 · Tomasi et al. 2013 · Jamadar et al. 2025

- *The integrative computation underlying deliberate choice is among the most energetically expensive the brain performs.*

● NEOCLASSICAL ECONOMICS

Neoclassical theory assumes cognition is costless

The canonical agent maximizes expected utility over a fully specified probability model:

$$a^{\star} = \arg \max_a \mathbb{E}_{p(o|a)}[u(o)]$$

Each component, **unbounded computation**, complete knowledge of the relevant $p(o / a)$, and instantaneous optimization, presupposes that inference has no cost.

- *These idealizations are jointly equivalent to setting the metabolic cost of inference to zero.*

● CONSEQUENCES

Two consequences of assuming costless cognition

Uncertainty is represented as risk

A costless agent can maintain full distributions over all outcomes, so uncertainty is modeled as risk with known probabilities. Genuine, Knightian uncertainty, with unknown probabilities, has no natural representation.

Behavior is described by equilibrium, not process

Instantaneous optimization to a fixed point is feasible only if optimization is costless. The temporal dynamics of perception, learning, and action are replaced by the equilibrium they are assumed to reach.

- *Both follow directly from setting the cost of inference to zero.*

● BEHAVIORAL ECONOMICS

Behavioral economics retains the costless benchmark

Behavioral economics documented systematic departures from the costless-rational ideal in detail. Because it retained that ideal as the normative benchmark, it characterized the departures as biases. Many of these patterns, including heuristics, satisficing, and limited attention, are the **expected behavior** of an agent operating under a metabolic constraint the benchmark does not represent.

- *On this account, many documented biases are signatures of resource-efficient inference rather than departures from rationality.*

II

An active inference account

Active inference describes an agent that minimizes variational free energy under bounded, metabolically costly precision. We use it to represent the constraint explicitly and to recover the structure of economic behavior.

● THE FRAMEWORK

Perception and action minimize one quantity

Active inference describes a whole agent under a single objective. The agent is a generative model of its world, and it reduces surprise in two ways:



Perception updates the model to fit the world; action changes the world to fit the model. Both minimize one quantity, variational free energy. **Precision**, the gain on prediction error, weights every error, and precision is the metabolically costly resource.

- *Unifying perception and action under one objective is what lets active inference describe an agent, not only a choice.*

● VARIATIONAL FREE ENERGY

The free-energy functional and the cost of precision

Formally, the agent minimizes variational free energy, an upper bound on surprise, written as a complexity term that penalizes departures from prior beliefs minus an accuracy term:

$$F = \underbrace{D_{\text{KL}}[q(s) \parallel p(s)]}_{\text{complexity}} - \underbrace{\mathbb{E}_{q(s)}[\ln p(o \mid s)]}_{\text{accuracy}}$$

Belief updates are weighted by precision, the gain on prediction errors. Sustaining precision is metabolically costly:

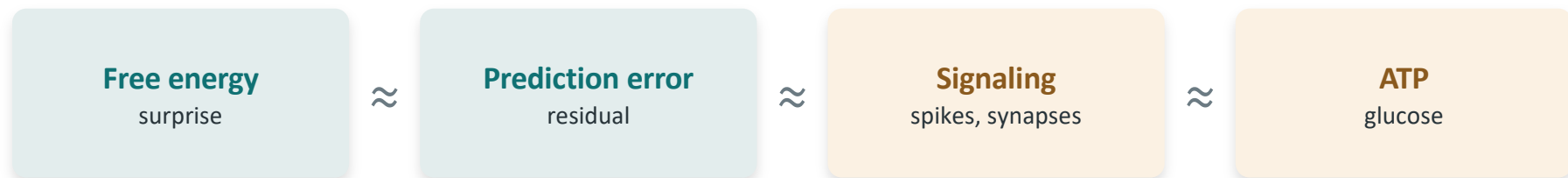
$$\dot{\mu} \propto \underbrace{\Pi}_{\text{precision}} \underbrace{\varepsilon}_{\text{pred. error}}, \quad \Pi = \Sigma^{-1}$$

- *Precision is the point at which the metabolic cost of inference enters the formalism.*

● PREDICTION ERROR AND ENERGY

Prediction-error minimization reduces the dominant metabolic cost

In predictive coding, only prediction errors are propagated; predicted input is explained away and not transmitted. Because synaptic transmission dominates the energy budget, reducing prediction error reduces the most expensive activity. The minimized quantity can be described at **several levels**:



Empirically, the additional cost of goal-directed cognition is on the order of 5% above resting baseline, consistent with a model that already predicts most input. Precision allocates the residual.

Sengupta, Stemmler & Friston 2013 · Zénon, Solopchuk & Pezzulo 2019 · Jamadar et al. 2025

- *Reducing prediction error and reducing energy expenditure are closely aligned objectives.*

● THERMODYNAMIC INTERPRETATION

Variational and thermodynamic free energy share a functional form

This correspondence is formal, not metaphorical. Variational free energy can be written as expected energy minus entropy, with the negative log model evidence in the role of energy, the form of a Helmholtz free energy:

$$F = \underbrace{\mathbb{E}_q[-\ln p(o, s)]}_{\text{expected energy}} - \underbrace{H[q(s)]}_{\text{entropy}} \equiv \underbrace{\langle E \rangle - T S}_{\text{Helmholtz free energy}}$$

Information processing also has a thermodynamic lower bound (Landauer): erasing one bit costs at least $k_B T \ln 2$ of energy. Efficiency, in bits per joule, is therefore bounded, and neural codes appear optimized for energy efficiency, favoring sparse, low-rate representations.

Sengupta, Stemmler & Friston 2013 · Landauer 1961

- *Free-energy minimization therefore has a consistent thermodynamic interpretation in terms of energetic cost.*

● ALLOSTASIS

Viability is regulated by prediction, not feedback

The agent does not merely hold the body at fixed set-points. It regulates the body by anticipating demand, the same free-energy minimization applied to the organism's own states.

HOMEOSTASIS

stability through constancy

The body reacts to deviations from fixed set-points after they arise, by negative feedback.

ALLOSTASIS

stability through change

The brain predicts metabolic demand and mobilizes resources in advance; set-points are themselves adjusted.

The predictive machinery exists to manage the organism's energy budget over time, anticipating need rather than reacting to depletion. **Economic behavior is this regulation externalized**, acting on the world to secure future viability.

Sterling 2012 · Pezzulo, Rigoli & Friston 2015 · Barrett & Simmons 2015

- *Time, risk, and saving follow from regulating viability forward in time, not from preference alone.*

● EXPECTED FREE ENERGY

Expected utility as a limiting case of expected free energy

Policy selection minimizes expected free energy, which decomposes into two terms:

$$G(\pi) = \underbrace{-\mathbb{E}_q[\ln p(o | C)]}_{\text{pragmatic: } - \text{expected utility}} \underbrace{-\mathbb{E}_q[D_{\text{KL}}[q(s | o) || q(s)]]}_{\text{epistemic: information gain}}$$

The pragmatic term corresponds to expected utility; the epistemic term quantifies expected information gain. Setting the epistemic term to zero recovers expected-utility maximization, which is appropriate only when information has no value.

- *Expected-utility theory corresponds to the limit in which the value of information is neglected.*

● SUMMARY OF CORRESPONDENCES

Economic constructs under a cognitive-cost constraint

ASSUMING COSTLESS COGNITION

Fixed, given preferences

Risk, with known odds

Bounded rationality, assumed

Choice, a static optimum

Exploration vs exploitation

The disembodied calculator

Atomistic markets



UNDER A METABOLIC COST

Priors: cached, economized inference

Uncertainty, native: ambiguity and precision

Bounded rationality, derived from cost

Perception and action as one process

Epistemic and pragmatic value

The living agent on an energy budget

Collective allocation of precision

● BOUNDED RATIONALITY

Bounded rationality as constrained free-energy minimization

The agent minimizes free energy together with the metabolic cost of the precision it employs:

$$\Pi^* = \arg \min_{\Pi} \left[\underbrace{F(\Pi)}_{\text{free energy}} + \lambda \underbrace{C(\Pi)}_{\text{metabolic cost}} \right], \quad \frac{\partial C}{\partial \Pi} > 0$$

At the optimum, the marginal reduction in free energy equals the marginal metabolic cost, scaled by λ , which functions as a shadow price on precision. Characteristic biases arise at the boundaries of this constrained optimum.

- *On this account, systematic biases are properties of constrained-optimal inference rather than failures of it.*

● PREFERENCES

Preferences as priors; utility as log prior preference

In the generative model, prior preferences form a distribution over outcomes, and utility corresponds to its logarithm:

$$u(o) = \ln p(o \mid C)$$

Preferences are thus components of the model rather than exogenous primitives. As priors they represent **cached inference**, reducing repeated computation; they are correspondingly stable, and revise when prediction no longer supports them.

- *This yields endogenous, learnable preferences and an explicit identification of utility with log prior preference.*

● COLLECTIVE INFERENCE

Markets as multi-agent inference

At the collective level, no single agent can maintain precision across all domains. Markets, firms, and institutions distribute the cost of precision across specialized agents whose generative models are coupled. Prices, norms, and conventions function as **shared priors** that coordinate expectations and reduce the inference each agent must perform.

- *This provides a route from individual to collective inference, connecting to work on collective intelligence.*

I II III

III

Open questions

The empirical premise is well established and the formalism is available; the economic theory built on their combination remains largely undeveloped. Several directions follow directly.

● STATE OF THE FIELD

A tractable and largely open synthesis

The relevant tools are mature: the formal apparatus of active inference, and methods for measuring neural metabolism at increasing spatial and temporal resolution. The corresponding synthesis in economics, joining this formal apparatus to the metabolic cost of cognition, remains largely unaddressed. The intersection is **well-defined and substantially open**.

- *Both the methods and the questions are well-specified; their combination has received little attention.*

● RESEARCH DIRECTIONS

Open problems

- A cost function $C(\pi)$ for precision, grounded in metabolism
- Precision allocation and the economics of attention
- Active inference models of markets and macro dynamics
- Preferences as cached inference: habit, taste, culture
- Multi-agent free energy: institutions and coordination
- Allostasis and viability as economic objectives
- Epistemic value as a theory of innovation and search
- Experiments linking metabolism, precision, and choice

● SUMMARY

Economics models choice; it has lacked a model of the agent

The agent is a physical system that must expend energy to infer and to act. Neoclassical theory omits this cost, behavioral economics interprets its consequences as irrationality, and active inference represents it explicitly, as bounded precision. Taking the metabolic constraint as primitive recovers much of the observed structure of economic behavior and defines a substantial research program.

- *The cost of cognition is a candidate foundation for economic behavior, and an open one.*



Cognition is metabolically costly, and that cost shapes economic behavior. Active inference provides a formal account of it.

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