The Cortical Markov Blanket: Stochastic Active Inference and Intrinsic Integrated Information (Letter)

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Abstract

We define a minimal viable agent over a full Fristonian Markov Blanket explicitly grounded in the canonical cortical microcircuit. By modeling the stochastic dynamics of a four-component system (internal, sensory, active, and external states), we rigorously demonstrate the conditional independence required by the Free Energy Principle via the steady-state Lyapunov equation. To evaluate intrinsic causal integration, we map the continuous stationary density to a discrete Transition Probability Matrix (TPM). We apply Tononi's Integrated Information Theory (IIT 4.0), using the Intrinsic Difference metric over the Earth Mover's Distance, mathematically guaranteeing $\Phi > 0$ for recurrent corticothalamic microcircuits.

1 Stochastic Neural Dynamics and the Markov Blanket

Following Friston [1], we partition the universe into four interacting states: internal (c_t), sensory (s_t), active (a_t), and external (λ_t). We ground this topologically in the canonical microcircuit for predictive coding [2]: s_t represents L4 thalamocortical inputs, c_t represents the recurrent L2/3 and L5 populations, a_t represents L5 deep outputs and L6 corticothalamic feedback, and λ_t represents the environmental hidden states.

The continuous dynamics are governed by a coupled system of Stochastic Differential Equations (SDEs) driven by standard Wiener processes:

$$dc_t = f_c(c_t, s_t, a_t)dt + \mathbf{B}_c dW_t^c \tag{1}$$

$$ds_t = f_s(c_t, s_t, a_t, \lambda_t)dt + \mathbf{B}_s dW_t^s \tag{2}$$

$$da_t = f_a(s_t, a_t, \lambda_t)dt + \mathbf{B}_a dW_t^a \tag{3}$$

$$d\lambda_t = f_\lambda(s_t, a_t, \lambda_t)dt + \mathbf{B}_\lambda dW_t^\lambda \tag{4}$$

Crucially, there is no direct coupling between c_t and λ_t. Linearizing the drift around a non-equilibrium steady state yields a Jacobian matrix $\mathbf{A}$. The stationary covariance $\mathbf{\Sigma}$ is uniquely determined by the Lyapunov equation:

$$\mathbf{A\Sigma} + \mathbf{\Sigma A}^T + \mathbf{BB}^T = 0 \tag{5}$$

The strictly block-sparse structure of $\mathbf{A}$ and $\mathbf{B}$ ensures that $p(c, \lambda \mid s, a) = p(c \mid s, a)p(\lambda \mid s, a)$, rigorously proving the existence of the Markov blanket.

2 Intrinsic Integrated Information (Φ)

To evaluate Tononi's Φ, we assess the intrinsic cause-effect power of the internal states c_t. We derive a discrete Transition Probability Matrix $\mathrm{TPM}(s' \mid s)$ from the exact Fokker-Planck stationary distribution $p(\mathbf{x})$ over a minimal timescale Δt, applying maximum entropy priors to the boundary conditions [4].

Using the IIT 4.0 framework [3, 4], we measure the irreducible intrinsic information across the Minimum Information Partition (MIP) using the Earth Mover's Distance (EMD) between the intact Cause-Effect Structure (CES) and the partitioned CES:

$$\Phi = \min_{\mathrm{MIP}} \mathrm{EMD}\left[\mathrm{CES}_{\mathrm{intact}},\ \mathrm{CES}_{\mathrm{MIP}}\right] \tag{6}$$

Because the internal cortical microcircuit (c_t) possesses strong recurrent loops (e.g., L2/3 $\to$ L5 and L5 $\to$ L2/3), the localized block of the Lyapunov covariance $\mathbf{\Sigma}_{cc}$ is strictly irreducible under any bisection. Consequently, the intrinsic difference is strictly positive, mathematically guaranteeing $\Phi > 0$ for biological cortical columns.

References

[1] K. Friston, *J. R. Soc. Interface* **10**, 20130475 (2013).

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[3] M. Oizumi, L. Albantakis, G. Tononi, *PLOS Comput. Biol.* **10**, e1003588 (2014).

[4] L. Albantakis et al., *PLOS Comput. Biol.* **19**, e1011465 (2023).