All quantum systems are strange: A commentary on "Path integrals, particular kinds, and strange things" by Friston, Da Costa, Sakthivadivel, Heins, Pavliotis, Ramstead, and Parr

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In "Path integrals, particular kinds, and strange things," Karl Friston and colleagues explore a number of implications of the classical "Bayesian mechanics" (Friston, 2019; Ramstead et al., 2022) induced by the Free Energy Principle (FEP). Besides being a mathematically and physically rich endeavour, the presentation further spotlights the FEP as a commanding scientific principle. We will focus on just one of these implications, the typology of qualitatively distinct classes of systems presented in Fig. 2 of Friston et al. (2023). We first review the relevant distinctions as they are presented, in terms of the causal connections between sensory and active states of the Markov blanket (MB) and internal and external states, i.e. states of the system A of interest and its physical environment B. We then consider what happens when the classical MB is replaced by a holographic screen, which serves the function of an MB in a quantum information-theoretic formulation of the FEP (Fields, Friston, Glazebrook & Levin, 2022; Fields et al., 2023). The most obvious difference between a classical MB and a holographic screen is that the states of an MB are elements of the state space of the "universe" of which A and B are components, while the states of a holographic screen are ancillary to this space. This difference, we will show, qualitatively distinguishes the classical and quantum formulations of the FEP. The distinctions between classes of systems illustrated by Fig. 2 of Friston et al. (2023), in particular, collapse when a classical MB is replaced by a holographic screen. Not only are all quantum systems active in the sense defined in Fig. 2, but moreover, *all* quantum systems are strange, and can be considered as 'inferring' their own actions as we will proceed to explain.

As employed in the FEP, classical MBs comprise two distinct sets of states: sensory states s and active states a. A system of interest A has internal states μ; its physical environment B has external (relative to A) states η. Describing the situation from B's perspective just requires exchanging s for a and exchanging μ for η. Distinct classes of particles (a "particle" is a system of interest plus its MB) correspond to distinct sets of causal arrows between these states. "Inert" particles have no arrows to or from a; active states effectively do not exist. The internal states μ of such systems have only incoming arrows $s \to \mu$ and so are information sinks. "Active" particles are characterized by arrow chains $\eta \to s \to a \to \mu$ and $\mu \to a \to s \to \eta$; here "sensation" is informative (to A) via "action" and vice-versa. "Strange" particles shorten these chains to $\eta \to s \to \mu$ and $\mu \to a \to \eta$ while maintaining the $s \rightleftarrows a$ cycle. Hence in these particles, sensation directly informs A (i.e. A's internal states) and action directly informs B, while the direct feedback links $s \to \eta$ and $a \to \mu$ present in active particles are broken.

Let us now change the formal setting from the classical physics of causal networks to the quantum physics of generic interactions between separable (i.e. non-entangled) systems. Consider a decomposition $U = AB$ of some isolated system U into a system of interest A and its complement $B = \bar{A}$, which is its total physical environment. The components A and B can only be unentangled if their interaction H_{AB} is weak, i.e. only if it involves relatively few of their degrees of freedom. In this case, we have both $H_{AB} = H_U - (H_A + H_B)$ and $H_{AB} \ll H_A, H_B < H_U$. As discussed previously (Addazi et al., 2021; Fields, Glazebrook & Marcianò, 2021, 2022a), we can, in this case, consider the decompositional boundary between A and B to be a holographic screen $\mathscr{B}$ with thermodynamic entropy $S(\mathscr{B}) = N = \log_2(\dim(H_{AB}))$, the minimum number of bits required to encode the largest eigenvalue of H_{AB}. Note that this boundary $\mathscr{B}$ is completely ancillary to the physical system $U =$

AB; we can assign $\mathscr{B}$ an effective Hilbert space $\mathcal{H}_{\mathscr{B}}$ with dimension $\dim(\mathcal{H}_{\mathscr{B}}) = 2^N$, but $\mathcal{H}_{\mathscr{B}} \cap \mathcal{H}_U = \emptyset$. Hence $\mathscr{B}$ performs the function of an MB – it restricts classical information flow from A and B to N bits – but it is from a physical point of view completely notional. It simply formalizes the fact that the interaction H_{AB} is weak enough that A and B are conditionally independent. As we have shown in Fields, Glazebrook & Marcianò (2021, 2022a,b), this observation is a reason why, in the classical limit, $\mathscr{B}$ approaches an MB.

Replacing the classical MB states s and a in Fig. 2 of Friston et al. (2023) with an ancillary holographic screen has a dramatic effect on the information flow between A and B. Inert systems are ruled out: an "interaction" H_{AB} in which information flows only one way is ill-defined. Active and strange systems become indistinguishable: both are characterized by interactions of the form $\eta \rightleftarrows \mu$, i.e. by generic A-B interactions that exchange N bits. They have, in particular, the defining characteristic of strange systems: actions on the environment are not directly observed, but can only be inferred from the environment's observable response. If A transfers N bits to B, in other words, it has to wait until it receives the next N-bit transfer back from B to learn anything about its action's effect on B.

The intuitive and somewhat reassuring behavioral distinctions that Friston et al. (2023) draw on the basis of the distinctions shown in Fig. 2 are replaced, in the quantum case, by strong and somewhat jarring no-go theorems (Fields, Glazebrook & Marcianò, 2021; Fields & Glazebrook, 2023). Not only can A not know the state space $\mathcal{H}_B$ or dynamics H_B of B, A cannot know her own state space $\mathcal{H}_A$ or dynamics H_A. The "self model" can only be a model, and can only be inferred from observations of the environment's behavior, where the "environment" is not just a source of uncertainty in a thermodynamic sense, but is also the repository of the system's stigmergic memories (Fields & Levin, 2023). Due to the thermodynamic cost of irreversible information processing, A cannot measure the dimension $\dim(\mathcal{H}_{\mathscr{B}})$, and hence cannot know the "size" or bandwidth of her interface with B. Perhaps most strikingly, A cannot measure the entanglement entropy $\mathcal{S}(AB)$ across $\mathscr{B}$, and so cannot know whether her state is separable from B's. Hence A cannot even know that she has a conditionally-independent state. To the "as if's" of Friston et al. (2023), therefore, we can add another: active inference agents act *as if* they can distinguish themselves from their environments. In quantum theory, at least, an agent cannot actually draw this distinction.

The ubiquity of strangeness clearly raises many questions, some verging on the mysterious. In the classical limit, the ancillary screen $\mathscr{B}$ is replaced by a classical MB. Do the states s and a of this MB "emerge" from A, B, or both? Can non-strange systems be consistently defined in this limit? What are the consequences, if any, of the answers to these questions in the neuroscientific context of Friston et al., or in others of the previously studied cognitive contexts cited therein, to which one might add various learning scenarios, e.g. Feature Selection (Pellet & Elisseeff, 2008; Guo et al., 2022) as alluded to in Fields & Glazebrook (2023)?

Conflict of interest

The authors report no conflicts of interest involved in this work.

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References

Addazi, A., Chen, P., Fabrocini, F., Fields, C., Greco, E., Lulli, M., Marcianò, A., Pasechnik, R., Generalized holographic principle, gauge invariance, and the emergence of gravity à la Wilczek. Front. Astron. Space Sci. 8 (2021) 563450.

Fields, C., Fabrocini, F., Friston, K., Glazebrook, J. F., Hazan, H., Levin, M., Marcianò, A., 2023. Control flow in active inference systems, Part I: Classical and quantum formulations of active inference. IEEE Trans. Molec. Biol. Multi-Scale Commun. 9, 235–245.

Fields, C., Friston, K., Glazebrook, J.F., Levin, M., 2022. A free energy principle for generic quantum systems. Prog. Biophys. Mol. Biol. 173, 36–59.

Fields, C., Glazebrook, J.F., 2023. Separability, contextuality and the quantum frame problem. Int. J. Theor. Phys. 62, 159.

Fields, C., Glazebrook, J.F., Marcianò, A., 2021. Reference frame induced symmetry breaking on holographic screens. Symmetry 13, 408.

Fields, C., Glazebrook, J.F., Marcianò, A., 2022. Sequential measurements, topological quantum field theories, and topological quantum neural networks. Fortschr. Phys. 70, 2200104.

Fields, C., Glazebrook, J.F., Marcianò, A. 2022. The physical meaning of the holographic principle. Quanta 11, 72–96.

Fields, C., Levin, L., 2023. Regulative development as a model for the origin of life and artificial life studies. Biosystems 229, 104297.

Friston, K., 2019. A free energy principle for a particular physics, Preprint arXiv:1906.10184.

Friston, K., Da Costa, L., Sakthivadivel, D.A.R., Heins, C., Pavliotis, G.A., Ramstead, M., Parr, T., 2023. Path integrals, particular kinds, and strange things. Phys. Life Rev. 47 35–62.

Guo, X., Yu, K., Cao, F., Li, P., Wang, H., 2022. Error-aware Markov blanket learning for causal feature selection. Inform. Sci. 589, 849–877.

Pellet, J.-P., Elisseeff, A., 2008. Using Markov blankets for causal structure learning. J. Machine Learn. Res. 9, 1295–1342.

Ramstead, M.J.D., Sakthivadivel, D.A.R., Heins, C., Koudahl, M., Millidge, B., Da Costa, L., Klein, B., Friston, K.J., 2022. On Bayesian mechanics: A physics of and by beliefs. Interface Focus 13, 2022.0029.