Physics as information processing
Course outline

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This six-session course will introduce participants to thinking about physical interaction as communication, and hence thinking about physical systems as communicating agents. It will show how the free-energy principle (FEP) and the idea of active inference apply to all physical systems, regardless of scale, subject only to constraints of conditional statistical independence or separability. It will investigate these constraints, their implementations, and their limits.

The course will introduce the formal methods of quantum information theory (QIT) and show how they relate to classical information theory. These methods will be employed as thinking tools, not calculating tools. A background in quantum theory or statistical physics will be useful but is not required; basic physics and some familiarity with linear algebra – vectors and operators – will be helpful. We will be discussing various abstract concepts, but with a focus on their intuitive meaning, not their formal structure No coding will be required, though anyone inclined in this direction will see many opportunities for model building.

There will be one "live" presentation session and one live discussion session per month, together with asynchronous Q&A and discussion. All sessions will be recorded and accessible asynchronously.

Session 1 (18 May) will review some history, starting with Boltzmann's relation between entropy and energy, and continuing through Church's and Turing's models of computation, Shannon's information theory, the "black box" methods of Ashby et al., Pearl's definition of a Markov blanket, Bekenstein's area law for black holes, 't Hooft's and Susskind's formulation of the holographic principle, the ideas of objects, interfaces, and virtual machines in computing, up to Friston's 2010 and 2013 papers introducing active inference. The goal of this session is to establish the idea of a Markov blanket as a communication interface.

Preparation: Wikipedia is a good general resource. If you are not familiar with them, review the Wikipedia articles on entropy, the Church-Turing thesis, information theory, and the Markov blanket. The first statement of the holographic principle is in Gerard 't Hooft's informal paper "Dimensional reduction in quantum gravity" (https://arxiv.org/abs/gr-qc/9310026). Karl Friston's papers "The free-energy principle: a unified brain theory?" (https://activeinference.github.io/papers/unified.pdf) and "Life as we know it" (https://royalsocietypublishing.org/doi/full/10.1098/rsif.2013.0475) are the key active inference references.

Session 2 (15 June) will ask: why use *quantum* physics to understand active inference? The answer is the discreteness of information and the necessarily limited resolution of all physical measurements. These naturally lead to a discrete-eigenvalue representation of interaction, i.e. to quantum theory. We will see how quantum theory generalizes the holographic principle, how holographic screens function as Markov blankets, and how all physical interactions between separable (non-entangled) systems can be viewed as communication. This answers the question "to what does the FEP apply?" with "everything measurable."

Preparation: Wikipedia has good articles on entanglement and on separable states (i.e. non-entangled states); both include more information than will be needed here. The first sections (through 3.1) of Fields, Glazebrook, and Marciano, "The physical meaning of the holographic principle" (http://quanta.ws/ojs/index.php/quanta/article/view/206) introduce this material. Friston's "A free energy principle for a particular physics" (https://arxiv.org/abs/1906.10184) discusses the generality of the FEP from a classical perspective.

Session 3 (13 July) will introduce the ideas of quantum reference frames (QRFs) and their representation using hierarchies of binary classifiers. These formal structures provide a semantics for measurements, and hence provide the basis for a theory of meaning for interacting agents. The language of QRFs allows a particularly straightforward and intuitive definition of variational free energy, and so allows a fully-general, quantum formulation of the FEP. We will see that the FEP is a classical limit of the principle of Unitarity, the fundamental principle of quantum theory.

Preparation: Sect. 3.2 and 3.3 of "The physical meaning of the holographic principle"; also Fields et al., "A free energy principle for generic quantum systems." (https://arxiv.org/pdf/2112.15242.pdf). Mike Levin and I relate these ideas to biology in "How do living systems create meaning?" (https://www.mdpi.com/2409-9287/5/4/36) and, with Jim Glazebrook, in "Minimal physicalism as a scale-free substrate for cognition and consciousness" (https://academic.oup.com/nc/article/2021/2/niab013/6334115?login=false).

Session 4 (10 August) will introduce the idea of a topological field theory, a field theory that does not assume a background spacetime. These provide a natural way to represent sequential measurements in terms of Feynman paths – i.e. of thinking about measurements as probing "every possible" way a system could have evolved. These methods allow a completely general description of multi-agent communication that allows the agents to employ both classical and quantum communication channels. We will focus here on how to think about composite agents, e.g. multicellular organisms and their nervous systems.

Preparation: Sect. 3.4 of "The physical meaning of the holographic principle" or for all the details, "Sequential measurements, TQFTs, and TQNNs" (https://arxiv.org/abs/2205.13184); additional reading TBA.

Session 5 (14 September) will introduce the idea that spacetime is an error-correcting code that organisms (or other observers) with sufficient computational resources use to organize their experiences. This makes spacetime observer-relative, and raises the question of what computational resources an observer requires to be able to "see" spacetime. It also shows that the FEP is intimately linked to the still-open question of how to formulate an acceptable quantum theory of gravity.

Preparation: John Wheeler's classic "Law without law" (https://psychonautwiki.org/w/images/3/30/Wheeler_law_without_law.pdf), Alexei Grinbaum, "How device-independent approaches change the meaning of physical theory" (https://arxiv.org/pdf/1512.01035.pdf), additional reading TBA.

Session 6 (12 October) will return to biology and summarize some applications, then point to future directions and open questions.

Preparation: Fields et al, “The free energy principle induces neuromorphic development” (https://iopscience.iop.org/article/10.1088/2634-4386/aca7de), “Control flow in active inference systems” (https://arxiv.org/pdf/2303.01514.pdf), additional reading TBA.