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ORIGINAL RESEARCH

Is the maximum entropy production just a heuristic principle? Metaphysics on natural determination

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Abstract

The Maximum Entropy Production Principle (MEPP) stands out as an overarching principle that rules life phenomena in Nature. However, its explanatory power beyond heuristics remains controversial. On the one hand, the MEPP has been successfully applied principally to non-living systems far from thermodynamic equilibrium. On the other hand, the underlying assumptions to lay the MEPP's theoretical foundations and range of applicability increase the possibilities of conflicting interpretations. More interestingly, from a metaphysical stance, the MEPP's philosophical status is hotly debated: does the MEPP passively translate physical information into macroscopic predictions or actively select the physical solution in multistable systems, granting the connection between scientific models and reality? This paper deals directly with this dilemma by discussing natural determination from three angles: (1) Heuristics help natural philosophers to build an ontology. (2) The MEPP's ontological status may stem from its selection of new forms of causation beyond physicalism. (3) The MEPP's ontology ultimately depends on the much-discussed question of the ontology of probabilities in an information-theoretic approach and the ontology of macrostates according to the Boltzmannian definition of entropy.

Keywords Maximum Entropy Production Principle · Interpretation of Variational Principles · Relationship between Heuristics and Ontology · Informational and thermodynamic Entropy · Physical and formal causality · Epistemic and ontological emergence

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1 Introduction

There are countless complex dynamical systems in the universe. Some of them present an astonishing degree of complexity and an archetypal example of this is the human brain. Unfortunately, it is well-known that no single specific theory for brain dynamics can predict, on its own, some of the latter's emergent features. At most, one must work with phenomenological approaches of limited scope that may not be coherently integrated into a broader picture, not least because of the diversity of relevant physical scales. However, as a complex system far from thermodynamic equilibrium, brain dynamics are expected to comply with the Maximum Entropy Production Principle (MEPP), one of the strongest candidates for being the overarching principle that rules life phenomena as far-from-equilibrium processes. In that case, emergent features of life, e.g., cognition, could emerge as MEPP's customizations.

Nevertheless, the status of the MEPP remains controversial. Firstly, there is the question of its application. Despite recent conjectures that biological systems evolve and organize themselves to maximize entropy production over the maximal spatial and temporal scales while abiotic processes maximize instantaneous and local entropy production (Vallino and Huber, 2018), the MEPP has been successfully applied mainly in non-living systems. Secondly, even if closely linked to the Second Law (SL), further assumptions are needed to establish the MEPP's theoretical foundations and range of applicability—near equilibrium steady states with carefully chosen external constraints—which can reduce the rigor of its predictions (Martyushev, 2010). This also increases the possible sources of confusion in its interpretations (Kleidon et al., 2010). Thirdly, and more interestingly for this contribution, the MEPP's epistemic status is subject to debate. For some, in the spirit of (Jaynes, 1980), MEPP passively translates physical information into macroscopic predictions (Dewar, 2009), providing a probability distribution of sorts for known constraints and a heuristic guide within the context of Bayesian inference (Dyke and Kleidon, 2010). For others, the MEPP reaches beyond heuristics (Martyushev and Seleznev, 2014), as it identifies the physical solution in multistable systems (Endres, 2017) and ensures its correspondence to reality (Glimm et al., 2020).

The present paper aims to tackle this controversy from a more fundamental, philosophical perspective: (1) It is not simply that heuristics and ontology meet at an impasse; the former helps scientists and philosophers construct the latter. (2) Even though one focuses on the explanatory power of the MEPP due to its capacity to inspire and generate effective models of non-equilibrium steady states—by, e.g., selecting the proper constraints at work in the system—one should not forget that such power may derive from the MEPP singling out new forms of causation. (3) The discussion regarding MEPP ontology undoubtedly depends on the difficult question of the ontology of probabilities in an information-theoretic approach and the ontology of macrostates in the Boltzmannian picture of entropy. Nevertheless, such interpretive issues are ultimately dependent upon the metaphysical problem of 'determination in nature' and, more specifically, whether natural causation encompasses microphysically efficient together with formally informative causes. In the case of the latter, new opportunities to understand the emergent features of non-equilibrium processes could arise.

The outline of this paper is as follows: Sect. 2 will explain the motivation behind the recourse to variational principles in the study of natural sciences and the position the MEPP occupies within the profusion of these. Section 3 presents the range of applications of the MEPP and how different constraints affect the former. Section 4 approaches the philosophical issue of how to interpret the MEPP beyond its technical success, particularly whether the MEPP points, beyond a heuristic role, towards new causal kinds in nature. Section 5 discusses how the ontological or epistemic status of the MEPP hangs on the interpretation of probabilities and macrostates in its informational and thermodynamic definitions, respectively. Finally, Sect. 6 makes the concluding comments.

2 The role of variational principles in natural sciences

The MEPP commonly appears as an optimization principle in which one physical quantity, namely, ‘entropy production,’ is maximized during a non-equilibrium process. Not being a state function—uniquely defined by initial and final states of the system—the precise value of said quantity depends on other variables and, most importantly, on the functional form (the ‘path’) that different physical quantities take during the timespan of the process. Such general dependence means that one can formulate the MEPP as a variational principle, similar to other well-known variational principles of physics such as the ‘least action principle’ (LAP). Once a closed mathematical formulation—including the relevant physical constraints for each particular problem—is achieved, habitual variation techniques produce the proper differential equations that govern the process of interest.

The history of variational principles in modern physics goes back to Fermat’s principle of ‘least time’ for a ray of light moving between two given points and culminated in the 19th century with a complete formulation of classical mechanics via the LAP. This stated that the integral of the Lagrangian of any physical system between two given points defining a time interval must be extremal. Such a requirement leads to the Euler-Lagrange equations that underlie classical mechanics. However, whereas variation principles easily coexisted with other formulations of classical mechanics, ultimately being reduced to Newtonian mechanics, their applicability to irreversible processes became controversial (Helrich, 2007). On the one hand, the relevance of the SL and time asymmetry in irreversible processes may raise questions about a transition from teleonomy to teleology for these processes (Sánchez-Cañizares, 2022a). While on the other hand, the global increase of entropy and mere irreversibility seems unable to produce a closed set of equations that can distinctly describe irreversible processes out of thermodynamic equilibrium.

Advances in non-equilibrium thermodynamics during the last century have toiled in incorporating similar variation principles for non-equilibrium processes (Jaynes, 1980). The MEPP is possibly the best example of this, even though its scientific status remains debatable at the present time. This is partly due to likely confusions regarding its applicability when compared, e.g., with Prigogine’s ‘minimum entropy production principle’ (mEPP) (Prigogine, 1961). Despite the optimism associated with the MEPP, it cannot be said to claim exclusivity in life sciences. It could be transformed or made redundant by different optimization principles that may capture life features better; for example the Free Energy Principle (FEP) (Friston, 2009, 2012, 2013, 2019; Friston and Stephan, 2007), or consciousness, such as the Integrated Information Theory (IIT) (Albantakis et al., 2022; Balduzzi and Tononi, 2008; Oizumi, et al. 2014; Tononi, 2008). To which extent these principles could be made compatible with and stem from an overarching variational principle[1] or, at the very least, suffice to characterize living systems in nature[2] remains unknown for the time being.

As it stands, one thing is clear; neither the LAP nor the SL serves to provide an operative framework for complex physical systems, with many degrees of freedom undergoing irreversible processes far from thermodynamic equilibrium. Said principles are but overall affordances for natural processes, particularly non-equilibrium processes, as those associated with life sciences. Nevertheless, something else is needed, at a principled level, to derive 'effective' theories for living systems. In other words, additional principles seem mandatory to determine the specific dynamics of far-from-equilibrium, complex systems. And it is here that the MEPP stands out as an unavoidable mediator between more general—LAP, SL—and more specific—FEP, IIT—variational principles.

3 Applicability of the Maximum Entropy Production Principle

Within the generic field of non-equilibrium physics, the MEPP can be applied in many different contexts. For instance, "the long-term mean states of the climate system of the Earth, those of other planets, and those of thermal convection and shear turbulence correspond, to a certain extent, to a unique state in which the rate of entropy production due to thermal and viscous dissipation is at a maximum" (Ozawa, et al., 2003, pp. 4–21). A special issue of the journal *Entropy*, edited by James Dyke and Alex Kleidon, dealt with this topic and its interpretations in 2009. However, its precise range of applicability and the new information it provided remain debatable. Needless to say, the MEPP is applied in life sciences, see, e.g. (Kleidon et al., 2010; Sawada et al., 2020; Vallino and Huber, 2018). Yet the question of what are considered appropriate timescales to be used for each problem arises. When applying the

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[1] Whereas IIT is an axiomatic account of consciousness, the FEP and MEPP have no such pretensions or axiomatic commitments. But the latter is not the main difference between said approaches. For instance, FEP seems to be a more general framework than IIT, as the former includes dynamics and (allegedly) encompasses any physical process entailed by living systems. IIT, however, provides a specific rule to identify a crucial life feature as consciousness, only assuming some physical dynamics conducive to the necessary informational relations in a conscious system. One may already see some attempts at embedding IIT in evolutionary dynamics (but not in an FEP framework) (Albantakis et al., 2014), and at combining IIT and FEP (Olesen et al., 2020). Even more ambitious would-be integrations (Safron, 2020).

[2] (Deacon, 2012) seems to deny the essence of such principles: "Organisms take advantage of the flow of energy through them to do work to generate constraints that block some dissipative pathways as compared to others. This is important because it shows that living organisms don't necessarily increase the rate of entropy production over some background inorganic rate." Of course, the crucial point here that, as far as we know, remains unclarified has to do with the possible dynamics, fully complying with the system's constraints, entering the comparison.

MEPP, is there an accepted time scale for biology that differs from other physical timescales? An intriguing general conjecture has recently appeared: “that biological systems evolve and organize to maximize entropy production over the greatest possible spatial and temporal scales, while abiotic processes maximize instantaneous and local entropy production” (Vallino and Huber, 2018). This conjecture may shed some light on the attempt to fundamentally discriminate between abiotic and biological systems. Yet, one may wonder whether the invoked difference between ‘greatest possible spatial and temporal scales and local ones’ is affected by (biological?) prejudices.

The fundamental issue raised in the previous paragraph brings our attention to the general topic of the MEPP’s range of applicability and, more importantly, general assumptions and constraints. In the literature dealing with the MEPP’s derivation, the latter and the SL are usually in close contact (Dewar, 2003; Martyushev and Seleznev, 2006; Ozawa et al., 2003). However, (1) additional, far-from-obvious assumptions for the mentioned derivation always have to be introduced. Besides, (2) the MEPP must be complemented with macroscopic physical constraints in order to be workable. (1) and (2) may be much more correlated than is commonly assumed, which adds to the potential sources of confusion—e.g., transient vs. steady state regimes, different physical fluxes involved, appropriate boundary conditions (Kleidon et al., 2010, pp. 1300–1301)—and the lack of rigor in its applications (Martyushev, 2010, pp. 1333–1334). For example, the apparent contradiction between the MEPP and the mEPP arises from the different constraints, either constant thermodynamic forces or fluxes, respectively, used to calculate and compare the entropy production in each of them (Martyushev, 2013, pp. 1159–1160). Under some circumstances, the different definitions of entropy production may also prove to be unequal (Županović et al., 2010, p. 1003).

Most authors agree on the technical requirements, in the spirit of (1), for the MEPP to be applied safely: the physical process must occur near its equilibrium state (Županović et al., 2010, p. 1003), making possible a local equilibrium representation of the system and the expression of the entropy production as a bilinear form of flows and forces (Martyushev, 2010, p. 1333). The MEPP will also most likely work in steady-state, far-from-equilibrium conditions, although some results in fluid mechanics when the Rayleigh number is large recommend caution (Martyushev and Seleznev, 2006, p. 27), not least because of the difficulty of analyzing and interpreting them.

Regarding specific problems, such technical requirements need to be combined with the appropriate selection of macroscopic physical constraints—our number (2)—which is significant from the point of view of the initial information at one’s disposal. This information relates to the system under investigation and may also determine (1)-conditions even further. Hopefully, the MEPP works predominantly for non-equilibrium systems in a steady-state regime. However, focusing on these regimes entails scleronomic constraints, i.e., constraints which are not dependent on time, which lead to no time-dependent Lagrange multipliers. Is this not too strict a condition for investigating life phenomena in general? How can more general processes with rheonomic, i.e., time-dependent, constraints and mixed regimes with several spatiotemporal scales be dealt with?[3] Criticisms of the FEP (Colombo and Wright, 2021; Longo and Montévil, 2014; Sánchez-Cañizares, 2021) in the line of organicism could consequently damage the MEPP's relevance and jeopardize its utility for understanding life (England, 2020; Swenson, 2000). The MEPP would also be vulnerable to accusations of sheer teleonomy and of true teleology in its description of the biological realm (Deacon, 2012).

4 Epistemic or ontological?

Relevant as the previous problems may be for the MEPP's progress in biology, they remain within the scientific discussion. However, from a more philosophical slant, one additional problem has emerged regarding its applicability. When carefully inspected, the problem relates to the epistemic or ontological value of the MEPP. As stated in the title of this contribution, is the MEPP just a heuristic principle, or is it additionally providing information about Nature's ontology? Such a question naturally arises when confronting Dewar's and Martyushev's interpretations of the MEPP.

According to Dewar, the MEPP is equivalent to Jaynes' Maximum Entropy inference algorithm from partial information (Dewar, 2009, pp. 932–933; Jaynes, 1957a, 1957b, 2003), in that the MEPP passively translates physical information into macroscopic predictions without introducing any additional assumptions itself. In other words, amongst the pool of probability distributions that comply with the problem constraints, the MEPP provides a rule to identify the most reasonable one. Even if different definitions of entropy and its related principles throughout history (Jaynes, 1980) may cast a shadow over such interpretation, in one way or another it is fundamentally dealing with Bayesian inference (Dyke and Kleidon, 2010). Hence the MEPP should be thought of as heuristics, a guide for setting up the most likely distribution of the system's microstates compatible with the macroscopic physical constraints. An analogy of this could be how the FEP allows determining the most likely dynamics for a system's internal states under its Markov blanket[4]. This interpretation could be called 'eMEPP.'

On the contrary, Martyushev strongly disagrees with the eMEPP. As a physical (ontological) principle, the MEPP would preferably be the crucial physical constraint, much like the SL or the charge conservation law (Martyushev, 2013, p. 1164). One may call the last interpretation 'oMEPP.' Whereas the eMEPP entails that one

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[3] An anonymous referee pointed out that the usual procedure to deal with said issue posits a separation of temporal scales, i.e., an adiabatic approximation. The system of interest over a slower timescale is described and averages the correspondent Lagrange multipliers to allow them to be time-invariant at said slower timescale. My point here, though, is not practical but fundamental. Such separation of time scales relies on an assumption about a steady-state solution for the system that Nature may or may not fulfill. In other words, life phenomena can be quite sensitive to the transient behavior between different steady-state regimes. Consequently, the assumption of a non-equilibrium steady state may miss crucial features in the evolution of life and the developmental stages of a living system.

[4] The epistemic status of the FEP is controversial too. (Bruineberg et al., 2022) presents an overall view of the discussion. See also the commentary (Sánchez-Cañizares, 2022b) on how the stipulation of Markov blankets may help to build an ontology. This topic will be part of the last section of the paper.

cannot disprove the MEPP, the oMEPP suggests that the MEPP can and should be tested in different experimental setups, thus being falsifiable. Moreover, the oMEPP would make the MEPP an overarching principle governing not only the evolution of non-equilibrium physical and chemical systems but also the biological evolution: at each hierarchical level, under the imposed constraints of the surrounding world, the system will choose the state with the maximum entropy production density. The MEPP would thus become a critical link to the increasing complexity of biological and social evolution (Martyushev, 2013, p. 1165). The oMEPP allows us to see the surrounding world from the same perspective without an acute division between the animate and inanimate. The formation of the higher levels in Nature also takes place according to this principle. Yet how many levels the surrounding world will eventually have and whether its construction will ever end is an intriguing question (Martyushev, 2013, p. 1166), which cannot be answered as of yet. It is one thing to claim that the MEPP draws on the formation of levels; it is another to explain Nature's hierarchical structure in a satisfactory manner.

Interesting to the eMEPP/oMEPP debate are recent contributions which have shown how the MEPP works in highly non-linear systems driven far from equilibrium, becoming the crucial tool to choose between the different steady states in a multistable system. The minimization of the classical and stochastic actions (equivalent to solving the dynamical equations) must be complemented with the maximization of entropy production, which biases the system evolution towards the highest-entropy-producing state. Even if, in itself, entropy production is not a unique descriptor of the steady-state probability distribution—where the underlying chemical or physical rules also play their role—the MEPP describes how the selection of steady states occurs in a multistable system (Endres, 2017). More rigorously, in the context of the Navier–Stokes and Euler equations for incompressible fluids, the MEPP becomes the inevitable one to select the physical solution. In other words, the MEPP can be seen as a necessary admissibility condition to ensure that the achieved answer is physically correct (Glimm et al., 2020). These findings present the MEPP as not wholly determining the physics whilst simultaneously being something more than heuristics, therefore pointing beyond the eMEPP.

5 The metaphysical stance on natural determination

In a sense, the discussion of the previous section need not surprise us with reference to entropy. In the words of Roger Penrose, "despite the admittedly confusing issues of subjectivity that are involved in our concept of 'entropy,' these serv[e] … merely to cloud the central mystery that underlies the profound usefulness of this remarkable physical notion" (Penrose, 2010, p. 43). Penrose himself is not free from the risk of contradiction by suggesting a somewhat arbitrary redefinition of entropy in black holes (Penrose 2010) and considering the Past Hypothesis, the astonishing tiny entropy of the Universe at the Big Bang, as "the most profound mystery of cosmology" (Penrose, 2016, p. 258; Sánchez-Cañizares, 2017, p. 908). It appears that we are entitled to tamper with the definitions of entropy, but not too much. In this concept, the epistemic tools of physics and the ontological structure of Nature seem to be inextricably correlated.

5.1 Metaphysics, heuristics, and ontology in optimization principles

As is well-known, different fields provide different definitions of entropy. In this subsection, we do not aim to review them or even offer examples for the sake of illustration. Nonetheless, we can refer to two distinct basic conceptual understandings of entropy: the informational and the thermodynamic. For instance, regarding the MEPP, some authors could be said to favor the thermodynamic definition (England, 2013, 2015, 2020; Horowitz et al., 2017; Swenson, 2000; Swenson and Turvey, 1991), and others the informational view (Dewar, 2003, 2005, 2009; Dyke and Kleidon, 2010; Jaynes, 1980). While the relationship between the two is quite closely-linked and, in some cases, can be shown to be equivalent[5], there are also some differences in how they depend on each other.

Indeed, in a strictly scientific procedure, one may stand by an informational view of scientific theories without necessarily calling on a fundamental role for information—e.g., as in the popular *it from bit* or the computational theories of Nature[6]. Yet, as philosophers of information have shown, the concept of information suffers from ambiguities, and the possibility of its naturalization remains controversial[7]. An encouraging channel of clarifying the status of information takes note of its underlying, thermodynamic causal paths which correlate in different ways, as pointed out in (Deacon, 2012). Briefly stated, the mere consideration of information as Shannon information forgets about its referential capacity that, in turn, depends on physical work that has, or could have, altered the state of some medium open to extrinsic modification. There is an additional criterion besides being susceptible to an 'extrinsic modification' that constitutes the referential value of an informing medium.

Even if we do not have a fully developed theory of reference yet, the previously outlined relationship between thermodynamics and information offers an indication to discriminate between the eMEPP and the oMEPP. (1) On the one hand, information in Nature needs an underlying physical base with thermodynamic properties working as allowances for referential information—i.e., not only possible but meaningful information. (2) On the other hand, as mentioned at the end of the last section, the information provided by the MEPP also allows for determining the physical regime actually performed by Nature. As we will endeavor to show, thermodynamics and information work together, at different levels, in natural determination.

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[5] Of course, one must consider the different coarse-grainings procedures to link thermodynamic and informational entropy. The equivalence is relatively straightforward in the case of quasi-classical coarse-grainings, where the thermodynamic entropy, as obtained from statistical mechanics, also measures the loss of information (Gell-Mann and Hartle, 2007). However, the emergence of quasi-classical realms in Nature cannot be understood fundamentally from scratch (Sánchez-Cañizares, 2016).

[6] See, e.g., Part Three, "Computation Writ Large," in (Mitchell, 2009).

[7] (Floridi, 2011, Chaps. 6–7) presents a rigorous, even if not wholly successful, attempt. Nonetheless, the general objections revealing the need for external interpretation of the underlying physics still seem pretty much at play (Searle, 1997, p. 17).

The last statement should not come as a surprise for those philosophers of science who assume an overall realism as their metaphysical stance and allow physics the important role of describing natural processes from a fundamental perspective. Nevertheless, said metaphysics does not yet manage to build an ontology that tells systems from their environment—how we humans register the world[8]. For the latter, many social and individual processes of registration become unavoidable, particularly those triggered by what strikes humans as being within our physical range of observation. To build an ontology of objects—the world 'taken in a certain way' (Smith, 1998)—additional epistemic prescriptions or information belonging to different epistemic levels of description must then be heuristically considered.

5.2 Which causality for the Maximum Entropy Production Principle?

If the claims of the last subsection are to be upheld, the following demand naturally arises: should informational principles be guaranteed any causal role at all? If ontology and heuristics belong to different realms, the question is meaningless. On the contrary, if heuristics help to build an ontology of the world, it seems plausible to investigate what makes it possible for the world to be taken in a specific way—e.g., as populated by far-from-equilibrium complex systems. The MEPP seems to play a crucial role in individuating such systems, at least in selecting the steady-state regimes that make them relevant to a certain concept of reality.

Defenders of the eMEPP may merely state that the MEPP works as a heuristic principle whenever relevant information is missing. For example, if only a group of macroscopic constraints can be known, the most reasonable assumption for the microscopic behavior of a system in a non-equilibrium steady-state regime stems from the MEPP. In other words, "the MEPP is only a cogent theory when one adopts a Bayesian interpretation of probability" (Dyke and Kleidon, 2010, p. 622). Therefore the "procedure itself cannot tell us what is and what is not relevant to formulating a model. It can only use the information that we give it, which it promises to use as effectively as possible" (Dyke and Kleidon, 2010, p. 628). Consequently, the eMEPP deems the MEPP a heuristic tool for building models. If all the information already present in the system could be registered, the MEPP would be dispensable. The update of information in the Bayesian procedure would only direct how to improve the description of the already extant fundamental dynamics.

Nevertheless, this need not be the only interpretation of the MEPP, nor the most thorough one. If, heuristically, the MEPP succeeds in picking out the actual physical state amongst the pool of a priori equally possible thermodynamic non-equilibrium regimes, this updating does not have to be restricted only to the informational content of the researcher but could also be a causal explanation of how and why Nature selects that specific regime. Whereas the eMEPP strictly separates the ontological aspect of reality and the epistemic access to it, uniquely granting causal interactions for the former, the oMEPP embraces the possibility that an initially heuristic procedure reveals the existence of causal powers beyond the initial conditions and the fundamental interactions of the universe. Selection of dynamics would amount to a type

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[8] Quite different from any state-of-the-art Artificial Intelligence, see (Smith, 2019).

of causality that allows for the ongoing process of natural determination and overcomes sheer determinism[9]. Contrary to the eMEPP, which eventually dispenses with information in the ontology, the explanatory strength of the MEPP for the oMEPP stems from the MEPP's causal power[10]. By doing so, the oMEPP weaves together thermodynamics and information. Even if each of them works at a different level of causality—the former in the physical, the latter in the formal[11]—both are necessary to understand natural processes.

5.3 Natural determination

Once we have presented the metaphysical dilemma and its more natural solution, it is worth looking back to the most basic formulations of the MEPP that inevitably involve mathematical expressions of entropy. The definition of entropy in terms of heat or other macroscopic thermodynamic quantities can be passed over because we are interested in the connection between microscopic and macroscopic variables, as it appears in the informational entropy and the Boltzmann formula, i.e., $S_{inf} = -\sum_i p_i \log p_i$ and $S_B = k_B \log \Omega$, respectively. What do the eMEPP and oMEPP imply regarding the interpretation of microstate probabilities ($\{p_i\}$) and the number of microstates (Ω), both compatible with a macrostate?

If the MEPP is interpreted according to the eMEPP, microstate probabilities in S_{inf} are our best bets regarding the actual microscopic configuration of the system which is compatible with some macroscopic constraints that allow us to define the latter. However, these probabilities need not refer to any physical property of the system. At most, one can remain agnostic about the ontology of microstate probabilities. The counting of microstates in S_B does not fare any better, albeit for a different reason: The ontology of macrostates can be forgotten, since a macrostate is a convenient way to assemble physical microstates that ease the extraction of relations

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[9] One oft-unspoken problem of determinism is its inability to account for true natural novelty. Consequently, determinism usually shares ranks with philosophical views that deny the reality of time. Such a problem does not arise if one considers causality as the self-determination of a singular and freely chosen optimality by Nature itself (Barrett and Sánchez-Cañizares, 2018).

[10] Recently, the technical literature has established a duality between the FEP and the constrained maximum entropy principle (Ramstead et al., 2022; Sakthivadivel, 2022), most clearly displayed in path integral formulations of the FEP (Friston et al., 2022). An anonymous referee has pointed out that the FEP brings in a relevant notion that changes the field of optimization principles, namely, Markov blankets. Such a notion, together with corresponding assumptions of conditional independence between internal and external states, allows for the description of the dynamics of internal states in terms of a variational principle based on a free energy functional of Bayesian beliefs about external states. In other words, there is a dual information geometry encoded in the internal states of the system: an intrinsic geometry that measures distances between probabilities of internal (physical) states and an extrinsic geometry that measures distances between probabilities of beliefs (about external states). How would my distinction between the eMEPP and the oMEPP affect the FEP's metaphysical interpretation? The crucial point from the perspective of causality (and of this paper) is whether the extrinsic geometry is reducible to the intrinsic one, in which case information is dispensable for the FEP, as it is for eMEPP, or is not. In the latter case, the FEP should be interpreted in line with the oMEPP, as active inference and the information encoded about the external world possess a causal, determinative influence.

[11] This kind of causation chimes with what historically has been called formal causation. There is a current revival of hylomorphic and neo-Aristotelian approaches to the philosophy of nature and the mind. See, e.g., (Owen, 2018, 2021; Simpson et al., 2018).

between phenomenological quantities, namely, phenomenological or ‘effective’ theories. The crucial point here is that, in the eMEPP, the world ontology can be reduced to a microphysicalism of sorts, whereas probabilities and macrostates belong to the epistemic realm of possible descriptions of the world which, however, remain strange to and isolated from ontology.

Does the oMEPP offer up improvements for our metaphysical interpretations of the MEPP? Yes, it does, in the following sense. If natural determination—that Nature determines itself in its physical quantities—occurs not only at the microphysical level but at mesoscopic and macroscopic scales, as suggested by recent results (Endres, 2017; Glimm et al., 2020), microstate probabilities ($\{p_i\}$) and the number of microstates (Ω) compatible with a macrostate should be understood differently. Since the oMEPP claims that the MEPP is more than a heuristic procedure to make sense of human observations, optimization of entropy production not only says something about the system’s concrete dynamics. The MEPP is ‘informing,’ meaning forming, selecting, or updating the actual dynamics of the system in non-equilibrium contexts with many other possibilities. Consequently, microstate probabilities ($\{p_i\}$) are not just epistemic gambles but natural, i.e., real, potentialities for the updating of the system, even though they need the formal trigger of formal causation, as suggested by the oMEPP. Analogously, a macrostate compatible with a number of microstates Ω refers not just to a convenient gathering of microstates for practical reasons; it may also refer to the emergence of some novel degree of freedom in Nature that, in its turn, constrains the initial phase space of microscopic degrees of freedom. It does this by selecting only those compatible with the new macrostate.

6 Conclusions

At the end of this paper, the reader may still be wondering whether this discussion, ultimately referring to the interpretation of variational principles in science, needs to focus on the MEPP. Why not focus on other principles, such as the LAP or the SL? A simple and practical answer gives leverage to the relevance of the MEPP for far-from-equilibrium natural processes as life or cognitive phenomena. Additionally, the MEPP relies on entropy, a quantity whose physical existence is hard to deny. While one could more easily consider physical action a mathematical construct to provide an alternative derivation of the differential equations that govern mechanics, entropy—not only through the SL but mainly via the MEPP—seems to have specific consequences in determining the physical processes taking place.

Nevertheless, studying the range of applicability of the MEPP and its most recent success has led us towards more fundamental issues regarding its possible interpretations, epistemic or ontological, and the more general problem of how to interpret variational principles in science, either as heuristics or as ontological principles, i.e., those which improve our knowledge about how Nature works. Variational principles like heuristics apply to select the actual process amongst a pool of (unrealized) possibilities. They do not need to drive physical processes or refer to dynamical laws. In natural systems, constraints may change so that the quantity optimized by variation becomes unrelated to ontologically previous values, i.e., to the actual process, even when describing the specific, steady-state, physical situation.

What one might initially consider a mere matter of philosophical taste—the metaphysical interpretation of variational principles—could have a more rational answer after paying attention to how the MEPP selects among potential physical regimes. We are therefore inclined to answer the title question of this paper in the negative. There are powerful reasons to claim that scientific endeavor is more than a matter of Bayesian inference. Surprisingly, these reasons aim to replace a metaphysically rigid conceptualization of causation with a structured co-determination of natural processes carried out by physical and formal causation. The (alleged) tension between efficient-physical and formal-informative causality may find a solution thanks to a different exercise of causation, in which information has an anticipatory role regarding physical (efficient) interactions and is crucial to system regulation and control. This metaphysical stance consequently embraces a causal role of 'information' in science, respectful of the underlying thermodynamics of physical processes, and equally distant from physicalism and *it-from-bit* panpsychism as insufficient causal monisms.

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Declarations

Conflict of interest The author has no relevant financial or non-financial interests to disclose.

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