(Some) Weather Probabilities are Ontic and Objective

Alexander Franklin[*]

March 10, 2025

Abstract

Probabilities play an essential role in the prediction and explanation of events and thus feature prominently in well-confirmed scientific theories. However, such probabilities are frequently described as subjective, epistemic, or both. This prompts a well-known puzzle: how could scientific posits that predict and explain human-independent events essentially involve agents or knowers? I argue that the puzzle can be resolved by acknowledging that although such probabilities are non-fundamental, they may still be ontic and objective. To this end I describe dynamical mechanisms that are responsible for the convergence of probability distributions for chaotic systems, and apply an account of emergence developed elsewhere. I suggest that this analysis will generalise and claim that, consequently, a great many of the probabilities in science should be characterised in the same terms. Along the way I'll defend a particular definition of chaos that suits the emergence analysis.

1 Introduction

What is the nature of the probabilities used in weather prediction? Given that meteorology and associated weather sciences are non-fundamental —

---

[*] alexander.r.franklin@kcl.ac.uk

they do not describe the world at its smallest length scales or highest energy scales — it's often thought that such probabilities are essentially epistemic or even subjective. I will argue that, notwithstanding their non-fundamentality, at least some such probabilities are ontic and objective. That is, they predict and explain the frequencies of weather events independently of any given agent's knowledge state, and they are the result of what I'll call 'objectification mechanisms' that secure inter-subjective agreement on their values. My account of objectification mechanisms relates closely to analyses developed elsewhere in the literature, especially those of Myrvold (2021) and Strevens (2011).

The paper starts with a discussion of chaos theory and the appeal to a chaotic model as a case study demonstrating how probabilities emerge in such contexts. I'll briefly discuss a quantum model of classical chaos to show that the initial conditions for chaotic analysis may be set stochastically as a result of quantum dynamics. If the input distribution is quantum and the chaotic dynamics lead to the convergence of a range of input distributions to the attractor distribution, then we have good reason to think of the final distribution as objective. In general chaotic attractors engender a choice of coarse-grained variables, with respect to which regular and reliable statistics may be observed. I'll then consider the extent to which this can be generalised among weather systems, noting in particular that the chaotic analysis and the claims of this paper are only relevant to some medium-term weather predictions.

I then relate my claims to the work of Hoefer (2019) and Sober (2010) to demonstrate that there are a number of accounts of the metaphysics of probabilities with which this is compatible and there is no good reason to presuppose any one or other of these for the project to proceed. In particular I argue that probabilities should count as chances (or 'ontic probabilities') insofar as they best explain and predict the observed frequencies. And these probabilities do just that.

The discussion then turns to the title claims: first, I demonstrate that the chaotic dynamics act as an objectification mechanism to take a very broad range of initial conditions to the same higher-level probability distribution – thus some weather probabilities are objective. Next I consider three routes to probabilities' counting as ontic, with the final route invoking an account of emergence (Franklin and Robertson (2024)). To insist that all non-fundamental probabilities are epistemic is a relic of an out-of-date metaphysical presupposition that only the most fundamental posits are truly ontic, but that's a rather infelicitous way to think about the world: for we would currently not know of anything to include in our ontology if that were the case. In fact, the probabilities considered here satisfy the criteria used in that account of emergence and should therefore be characterised as ontic.

I draw a contrast with the claims of Frigg and Hoefer (2019) and Loewer (2023) who suggest that many of the probabilities in physics are derivable from probability distributions over the initial conditions. While our analyses overlap, I argue that the emphasis should be placed on emergence and the required coarse-graining procedures given that just about any distribution over the initial conditions will do. I contend that this obviates any mysteries associated with the apparently epistemic nature of the distribution over initial conditions.

Lastly, I conclude with some potential upshots of this analysis: various legal attempts to extract compensation from historically high-emitting nations and companies for damages resultant upon extreme weather events rely on comparisons between the probability of such weather events given current CO_2 emissions and a counterfactual scenario in which emissions were much lower. This strategy implicitly relies on the assumption that such probabilities are objective and ontic probabilities. In slogan form, changes to epistemic probabilities cannot change the world. So the argument here ought to help shore up such cases.

Given the existence of the extensive literature on non-fundamental probabilities and deterministic chance (see e.g. Glynn (2010) and List (2018)) what does this paper add? I return to this in §5, but the short answer is that the focus elsewhere has been on legitimising the status of non-fundamental probabilities by appealing to features probabilities are taken to have and suggesting that these may be associated with non-fundamental theories. My goal here is to show how it is that underlying theories can give rise to the statistics with which probabilities are associated – as such, this should be complementary to claims in the deterministic chance literature and should strengthen the arguments there. If one can demonstrate the processes by which objective statistics emerge then non-fundamental probabilities should be an easier sell!

The upshot of this paper is a how-possibly explanation: apparently stochastic/probabilistic systems are all around us, and yet many of our more fundamental theories are deterministic. There is certainly a significant role for deterministic evolution in many physical systems, this explains why probabilities are often ascribed to our ignorance or related epistemic factors; but ignorance doesn't account for all the roles probabilities play in explanation and prediction: rather, ontic and objective probabilities are associated with the regular and reliable statistics (with respect to certain coarse-grained variables) that emerge as a result of the dynamics of various physical systems.

2 Probabilities from Chaos

2.1 Defining Chaos

Chaotic systems provide a helpful case study for this paper. In the following I'll explain how probabilities emerge for such systems, this analysis relies on three features characteristic of such systems: sensitive dependence on initial conditions, attractor dynamics, and mixing – together these provide reasons to doubt that probabilities are epistemic and underwrite the objectivity of probability distributions. While these features are instantiated by many chaotic systems, it's worth seeking a more general definition of chaos, this will help clarify the sense in which chaos is a level-relative phenomenon and will accord with the emergence analysis provided in §4.

The definition of chaos is hugely contested. Three worries face characterisations of chaos. First, if any real system is continually buffeted by external noise, and its initial conditions are likely to be affected by quantum mechanics, then do any real-world systems properly fulfill the determinism constraint standardly included in definitions of chaos? Second, is the characterisation of chaotic systems as unpredictable (commonly found in the literature, though not in Zuchowski's table) purely an epistemic matter? Third, how do we make sense of the dual criteria often employed in definitions of chaos? As can be seen from table 1 chaotic systems are both periodic and aperiodic, or both ordered and disordered. I'll develop each worry in turn and then suggest an account of chaos which addresses such worries.

It's common to include the stipulation that the underlying dynamics are deterministic as a necessary condition in standard accounts, as emphasised in Zuchowski (2017)'s comprehensive analysis. For example, she notes that May and Oster (1976) start their seminal discussion by contrast-

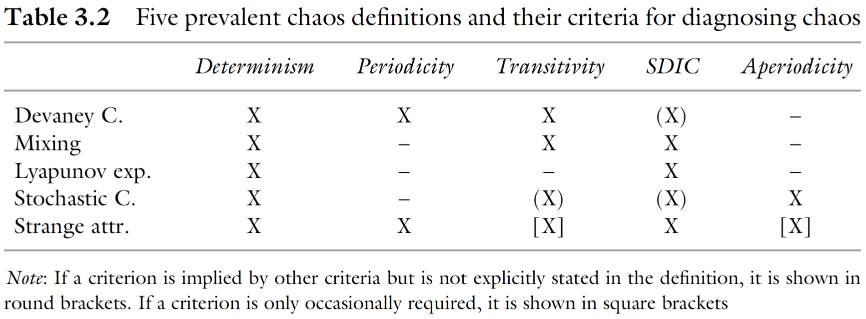

Table 3.2 Five prevalent chaos definitions and their criteria for diagnosing chaos

	Determinism	*Periodicity*	*Transitivity*	*SDIC*	*Aperiodicity*
Devaney C.	X	X	X	(X)	–
Mixing	X	–	X	X	–
Lyapunov exp.	X	–	–	X	–
Stochastic C.	X	–	(X)	(X)	X
Strange attr.	X	X	[X]	X	[X]

Note: If a criterion is implied by other criteria but is not explicitly stated in the definition, it is shown in round brackets. If a criterion is only occasionally required, it is shown in square brackets

Figure 1: From Zuchowski (2017, p. 67).

ing chaos with randomness: while both are unpredictable, chaotic systems' in-principle derivability from deterministic dynamics means that the unpredictability may be claimed to be in practice rather than in principle. Zuchowski goes on to say that aperiodicity is regarded by many as the defining feature of chaotic processes but this should be understood as akin to a Bernoulli process, and so it amounts to our system's being indistinguishable from a process taken to be 'genuinely stochastic'. It's interesting that chaos is thus defined as the combination of underlying determinism with effective stochasticity in contrast to fundamental/irreducible stochasticity. But what hangs on that distinction? Why ought we to insist that truly chaotic systems could not be irreducibly stochastic? Moreover, we can never establish that the underlying dynamics are in fact deterministic given the apparent stochasticity of the state of our system. In addition, extrinsic perturbations and fundamental quantum behaviour both suggest that determinism may be an artefact of our models and that the world to which the models refer lack this feature.

One way of justifying the necessity of such criteria is to posit a substantive distinction between ontic and epistemic probabilities and to claim that chaos is only found in contexts where the probabilities are epistemic, but it's this that I wish to deny. Rather, I will argue in this paper that ontic probabilities may be found at many non-fundamental levels of reality and that one need not discover the nature of the fundamental dynamics in order to characterise a system as featuring them. In part I think this is important because chances play a role in our scientific predictions and explanations, while the question of fundamental determinism is not settled. The same argument establishes that, given the difficulty of establishing that the fundamental dynamics for any given system are in fact deterministic, and the observation that many real-world systems are well modelled as chaotic, we should regard such worldly systems as in fact chaotic irrespective of the nature of their fundamental dynamics.

Another central feature of many definitions is sensitive dependence on initial conditions (SDIC). Any point in the phase space described exactly will, with deterministic dynamics, have a uniquely determined subsequent path through the space, and thus a unique trajectory; and yet if one takes a limited ensemble of initial points, close together to one another, they will in general exponentially diverge and, after a period of time, end up arbitrarily far apart. This corresponds to any system that has a positive Lyapunov exponent. Define the initial distance between two systems in the state space to be $\delta Z(0)$, then we can say that at time t the distance between two systems will be $\delta Z(t)$. $|\delta Z(t)| \approx e^{\lambda t}|\delta Z(0)|$ where λ is the Lyapunov exponent, and $1/\lambda$ is the Lyapunov time.

This prompts a puzzlement shared by many authors: if systems are deterministic then surely chaos is somehow an epistemic matter: it's to do with cognitively/computationally limited agents' predictive power. Kellert (1993) develops a response to this focussing on the fact that this predictive failure is in some sense built into the world: more atoms than there are in our galaxy would be required for certain predictions. But I don't think this gets quite to the core of why this isn't just an epistemic matter.

I propose rather to characterise chaotic systems by disregarding the most fundamental/precise description altogether; while this aspect of analysis is essential to the construction of many model chaotic systems it may be viewed as an idealisation that does not have a counterpart in the real-world systems modelled.

Chaotic systems, described after the onset of chaotic behaviour (e.g. after the Lyapunov time) *combine mid-level unpredictability with higher-level stochastic predictability.* That is, a feature shared by at least a great many chaotic systems is that if one slightly coarse-grains the initial condition – chooses a starting variable that is not exact, but includes a distribution of initial conditions (even if this is very constrained), the evolution of that distribution will be unpredictable: this is the straightforward consequence of SDIC which Kellert (1993) claims is generic among all chaotic systems. But at the higher level the right variables will allow stochastic predictability: in other words the system exhibits statistical regularities.

This account – the combination of mid-level unpredictability and higher-level statistical regularity – helps resolve the worries spelled out above.[1] First, we do not need to commit to any characterisation of the system at its most fundamental, and thus whether or not it is deterministic is irrelevant to the question of whether it is chaotic. Second, worries that chaotic probabilities must be epistemic are partially resolved by observing that the matter is scale- or level-relative whereby the probabilities may be ontic even if they do not feature in a more fine-grained description; the connection to emergence enables this analysis, while other discussions leave out this aspect. Third, the level-based analysis of this definition establishes how it could be that chaotic systems are both predictable and unpredictable or periodic and aperiodic, as Zuchowski (2017) explains. Chaotic systems are those where whatever the more fundamental dynamics, high-level statistical regularity emerges from mid-level unpredictability.

This is closely related to Smith (1998, p. 13)'s account: "This type of combination of large-scale order with small scale disorder, of macro-predictability with the micro-unpredictability due to sensitive dependence, is one paradigm of what has come to be called 'chaos'." Werndl (2009) objects to Smith's account by noting putative formal systems that satisfy the account but aren't chaotic, but I am not aiming at necessary and sufficient conditions for chaos. Rather, I hope that this account will be useful in deciding whether *wordly* systems count as chaotic or not – a significant drawback of more formal accounts is that they require the fulfilment of specific mathematical criteria, where it's often unknowable whether or not such criteria are in fact fulfilled by real-world systems. So the fact that my account is more inclusive than Werndl's should not bother us; note that my account is also more inclusive than Smith's (thus avoiding Werndl's other objections) because I merely require stochastic rather than absolute predictability.

2.2 Characteristic Features of Chaotic Systems

If we accept a heuristic definition along these lines, we ought to wonder: how is it that chaotic systems do achieve this combination of unpredictability and statistical regularity? This turns out to be a consequence of their

---

[1] The connection to Batterman (2021) and the focus on mid-level variables there should be apparent.

dynamics. In particular, the dynamics of chaotic systems generally exhibit two features: attractors and mixing on the attractor. In combination these establish that, irrespective of the starting position after some amount of time, the distribution will evolve into a subregion of the initial phase space and then spread out over that entire space with an equal measure in each subregion, thus allowing that with respect to a partition over that space the system will exhibit statistical regularities. In some more detail:

Attractors correspond to "a region of phase space to which all nearby trajectories or points of a model eventually tend" (Zuchowski (2017, p. 74)). This is possible for dissipative systems as their phase space volume is not conserved; the damped pendulum is a paradigm example of this. A subclass of attractors are known as 'strange', these are systems that are attracted to a set of phase space points that are called 'fractal'; Grebogi, Ott, and Yorke (1987): "there can be an arbitrarily fine-scaled interwoven structure of regions where orbit trajectories are dense and sparse".[2]

Mixing is defined precisely and in detail in Werndl (2009) but for our purposes we just note the consequence of mixing that after sufficient time any initial distribution is spread equally over the entirety of the relevant region of the phase space: "[i]ntuitively speaking, the fact that a system is mixing means that any bundle of solutions spreads out in phase space like a drop of ink in a glass of water" Werndl (2009, p. 204). However mixing only holds for measure-preserving dynamical systems, which means that no dissipative system that evolves under attractor dynamics is mixing. That's why the combination of the attractor dynamics, which takes the system to (or arbitrarily close to) the attractor, plus the mixing over that attractor, work in concert to establish that irrespective of starting point we have statistical predictability. While Werndl argues that mixing is necessary and sufficient for chaos, it's helpful to note that a chaotic system can start far away from the attractor (where mixing doesn't hold), evolve chaotically, and end up with regular statistics. Note also that approximate mixing is in general sufficient for behaviour to be classed as chaotic.

My preferred definition of chaos thus underwrites the coarse-grained periodicity: there are regular or predictable features of chaotic systems at the coarse-grained level as a result of the attractor and (approximate) mixing even if at the more fine-grained level we have unpredictability and aperiodicity. Both the iterated logistic model and iterated Lorenz model

---

[2] Zuchowski notes that strange attractors are just those attractors that, in combination with other criteria, such as SDIC are sufficient for chaos.

can be formally shown to have attractors, and the butterfly-shaped discrete Lorenz model also has a clearly identifiable attractor (Zuchowski (2017, §3.4.5)).

Given the diversity of approaches in the literature, it seems unlikely that any one definition will include every model or worldly system that has been regarded as chaotic, so chaos seems to be a cluster concept. But there are advantages to my approach, not least that it has worldly (material mode) applicability whereas a more mathematised conception may only be theoretically applicable (formal mode). In addition, the above discourse provides a comprehensible account concerning the emergence of statistical regularities from chaotic systems.

For example, on the most simplified Lorenz model, if one chooses two variables corresponding to $x < 0$ and $x > 0$ the system will exhibit regular statistics; see figure 2 which illustrates the system's regularity for unforced and forced Lorenz dynamics. The attractor dynamics takes a distribution over initial conditions to reliable frequencies and thus, as will be argued, objective probabilities over some coarse-grained variables. More will be said shortly about the input distribution.

Chaotic systems provide an interesting case study that demonstrates the (effective) irrelevance of the starting point and the convergence of probability distributions. What's crucial is that a vast range of initial distributions converge upon evolution under the chaotic dynamics. If we choose the higher-level variables judiciously – the right coarse graining – then we can be assured that we'll have reliable higher-level statistics.

As will be discussed in more detail below, emergence centrally involves screening off. So, the later probability distribution must somehow be screened off from lower-level details. SDIC is an effective mechanism for this to occur. This is similar to what goes on in the die case discussed by Strevens (2011): the dynamics are such that even a very small imprecision in the specification of the starting point is sufficient to lead to a uniform distribution over the outcome variables – e.g. the faces of a die. Chaotic systems are important case studies because it's not the case that extra detail will allow for improved predictions or explanations of the type of outcome, though in a limited sense they may allow for in-principle improvements in token predictability.[3] Thus, as will be developed below these cases under-

---

[3] Note though that if the computation would require more resources than there are in the galaxy then it's not clear that this is even in-principle possible.

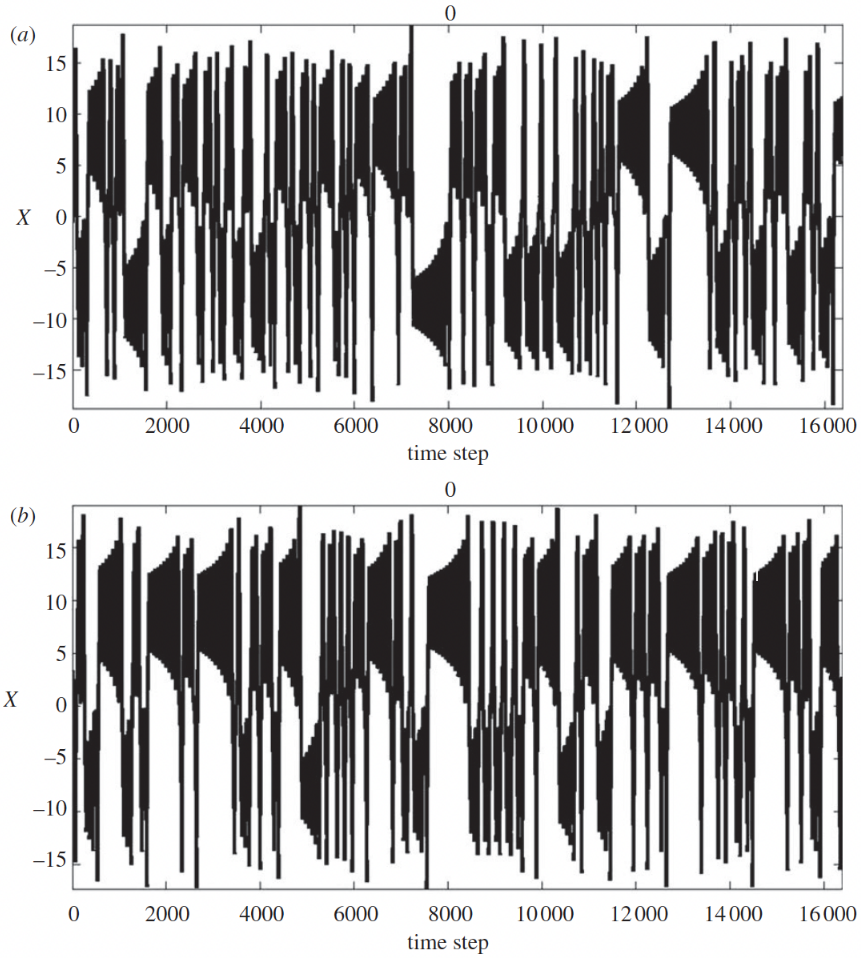

Figure 6. Examples of the time series of the X variable in the Lorenz model, evolving on the Lorenz attractor for (a) no external forcing and for (b) strong external forcing. Changes in probability of the upper regime/lower regime are affected predictably by the imposed 'forcing'.

Figure 2: From Slingo and Palmer (2011, p. 4759).

mine the view that non-fundamental probabilities must be understood as epistemic.

2.3 Input Distributions

The upshot of analyses of chaotic dynamics is that just about any initial position evolving under such dynamics will end up on the attractor, and if one chooses coarse-grained variables appropriately we will end up with robust statistics with e.g. even chance of finding our system on the right or left hand side of the Lorenz model. I'll return below to the question of whether or not such robust statistics signal the existence of corresponding probabilities. However, for now, the question is whether we've smuggled in some statistical assumptions in order to end up with probabilities. And the answer to that question is that of course we have. It is a corollary of Curie's principle that deterministic evolution of a single input cannot give rise to multiple distinct outcomes, and thus cannot support statistical regularities. However, what I'll show in this subsection is that this is an unrealistic model of real-world processes: that even in principle physically realistic chaotic systems should not be thought of as instantiating the deterministic evolution of an arbitrarily well-defined input.

What justifies the focus on chaotic dynamics (in analogy to focus on approach to equilibrium for statistical mechanical systems) is that a huge range of initial distributions will converge on the same distribution, where the degree of convergence exponentially increases with time. That's because of the attractor dynamics. What conditions on such inputs are required in order to lead to the robust statistics? The answer is that they aren't fine-tuned in some way or other as to avoid the attractor region of the phase space. I'll consider two ways to ensure this holds: external perturbations and quantum mechanics, both of which also provide a source for the input distribution.

External perturbations, as discussed extensively by Strevens (2011) in the guise of 'noise' will interfere with a system and unless these themselves are correlated will push almost any system off the overwhelmingly rare attractor-avoidant trajectories onto those that lead to the attractor and hence exhibit the robust statistics. The fact that the systems we're considering exhibit SDIC means that just about any minor perturbation will be sufficient to disturb a system in a fine-tuned initial state.[4] Of course this is not absolutely guaranteed and so we can say that with very high probability a system subject to external perturbations will be such that its distribution converges to the attractor.

One might still enquire: what's the nature of the assumption that the systems do not start out correlated? Or relatedly, might the external perturbations be themselves fine-tuned? Frisch (2023) engages with this question and suggests that this is an additional condition one can impose on individual systems, or if one's ambitions are grander this can be generalised to the initial condition of the universe. This is closely related to Price (1997)'s condition PI^3: the Principle of the Independence of Incoming Influences. There's an extensive literature on the nature of this as a boundary condition of the universe, but all that needs to be said for our purposes is that this does seem to be a principle obeyed by physical systems in the universe and as such shouldn't offer grounds for scepticism concerning the project developed here.

The alternative source of the distribution over initial conditions that's relevant for chaotic systems is found in quantum mechanics. As developed in detail in Franklin (2023) building on modelling developed by Habib, Shizume, and Zurek (1998) and further analysis in Wallace (2012), classically chaotic systems are emergent from quantum mechanics via decoherence. It's argued there that the best way to understand this according to the Everett interpretation is as a sequence of worlds emerging sequentially, with slightly different starting conditions. As all systems are fundamentally quantum mechanical and on Habib, Shizume, and Zurek (1998)'s models quantum mechanical simulations can give rise to classical chaos, it seems appropriate to think that at least some, if not all, chaotic systems have their initial conditions determined at least in part by such quantum processes. It's important to note that while the analysis can be used to understand the Everett interpretation, no such assumptions are involved in the simulation itself and this should thus be relevant to many standard interpretations of quantum mechanics.

If the input distribution is specified by quantum mechanics, then one might worry that not much progress has been made. The nature of probability in quantum mechanics is famously vexed, and this issue is most

---

[4] Note, however, that the input distribution must be smooth for the convergence results to apply, and so the noise may not be seen as discrete knocks to the system; thanks to Ben Feintzeig for pressing me on this point.

pressing in the Everett interpretation. However, not all problems can be solved here. And if the upshot of this particular analysis is that the statistics of chaotic systems are traceable, via the chaotic dynamics, to the probability distributions of quantum mechanics, which at least have well-defined and agreed upon robust statistics, then surely progress has been made: though note that the convergence results establish that the chaotic distribution will not, in general, match the input distribution.

In sum, both noise and quantum mechanical inputs give us reason not to posit an exact point as the initial condition for a chaotic system in order to predict system outcomes: either the initial distribution is inherited from that of quantum mechanics, or the initial condition is arbitrarily precisely specified but the distribution is generated as external perturbations knock the system off its initial trajectory.

2.4 Weather

There's an interesting and extensive discussion in Zuchowski (2017) in which she analyses the evidence for thinking that real-world systems are in fact well described as chaotic. She concludes that there are good reasons in some contexts, but it's still somewhat an open question. However, as discussed above, the worries regarding the applicability of chaotic models are closely related to questions of fundamental determinism. If my preferred definition, advocated above, is adopted these worries are at least partially defused.

How about weather systems? I tendentiously titled this paper with reference to 'some weather probabilities', partly because the analysis of the statistics of weather and how these change is of pressing contemporary relevance to modelling the effects of climate change. So it's interesting to note the work of Tim Palmer (see e.g. Palmer (2019)), who has been instrumental in the introduction of ensemble forecasting and the consequent improvement of weather prediction models. Palmer argues against the assumption that the introduction of probabilities to weather prediction is purely epistemic, or due to our ignorance.

What seems to be generally accepted (see Buizza (2002) and Shen et al. (2021)) is that weather models exhibit features of chaos at least in the medium term, though the more involved answer notes that weather systems involve aspects of order and chaos in various regions. In the longer term they may be thought of as cyclical, and at the time period where weather becomes climate it's certainly possible to have more specific predictability than chaos would allow. On the very short term, weather is also less chaotic: if it's raining right now and the sky is full of dark clouds, I can be very confident that it will still be raining shortly. However, the chaotic dynamics of weather systems preclude deterministic predictability to increasing extent as the time exceeds the Lyapunov time (thought to be approximately 2 weeks for certain weather systems Zhang et al. (2019)), and leave us relying on the emergent statistics.

Palmer, Döring, and Seregin (2014) further suggest that some turbulent systems are intrinsically stochastic. While I do not have sufficient space to explore this literature in detail in this paper, it's worth noting here because it suggests that an additional set of weather/climate probabilities are both ontic and objective. The suggestion there is that even with arbitrarily high computing power there wouldn't be a way of perfectly predicting outcomes. "Errors in large-scale variability can be sensitive to errors in small-scale components of the flow. This argument indicates that minimizing systematic errors in the representation of large-scale processes requires minimization of systematic errors in the representation of small-scale processes." (ibid. p 465) The consequence of this is that no matter what one does at the large scale there will still be uncertainty, and that this is a consequence of the dynamics, however the literature does feature dynamical arguments for the convergence of distributions that would justify the attribution of objective probabilities to such systems.

The claim here is that in the medium term probabilities involved in weather prediction could not be improved by better computation or more accurate measurements (at least within any reasonably achievable constraints). Yet answers to the question 'is it raining in London on Tuesday 9-10am?' are distributed statistically in the medium term and the probability distribution is a consequence of features of the dynamics that make it robust with respect to a vast range of perturbations to the input conditions and the system as it evolves.

2.5 Probabilities from Statistics

Once we have established the existence of robust statistics for non-fundamental systems the question remains whether there are probabilities in such cases. By robust statistics I mean to refer to the feature exhibited by real-world systems whereby there are variables with respect to which there are, if one samples over a sufficient period of time, a ratio of values that is approximately constant. It's on the basis of such observations that probabilities are posited: probabilities explain and predict the observed statistics. But one might ask whether this is sufficient for the existence of probabilities.

A subjectivist about probability would be happy to grant that they are to be found in any such systems, but in the interest of a realist metaphysics, I restrict attention here to ontic probabilities, or chances. Can we find those wherever there are such statistics? Elliott and Emery (see e.g. Elliott (2021) and Emery (2015)) have recently written at length to defend the claim that one can: ontic probabilities provide the best explanation of the existence of reliable statistics – they predict the outcomes for any sequence of experiments and explain why certain sequences occur with greater or lesser frequency than others. In short: probabilities play an ineliminable role in scientific prediction and explanation. Therefore, we have as good a reason to posit them as any other scientific ontology. Analogous reasons should lead us to posit probabilities as to posit electrons or black holes: they allow for predictions and explanations without which we would be scientifically far worse off.

Two worries remain. First, one might think that probabilities are fundamentally different from other such posits because they are essentially modal. That is, the values of probabilities are, by their very nature, underdetermined by the distribution of categorical facts. In principle, for example, a coin could land heads every time, while it had a 50:50 chance of landing heads or tails. The probability of such a sequence would be astronomically small, but that does not usually imply that it's impossible (consider that the probability of any individually specified sequence is equal and yet one sequence must occur!) I think that the response to this worry will depend on background commitments in the metaphysics of modality, and as such I leave this open. It's also worth noting that the project developed in this paper should still be interesting to one who refuses to countenance any ontic probabilities at all – I demonstrate, at least, how it is that objective statistical patterns emerge.

The second and related worry concerns the metaphysics of such probabilities. If they're non-fundamental and thus do not feature in the fundamental laws of nature, how ought they to be analysed? This paper aims to be neutral with respect to this question – propensity, Humean, and frequentist accounts, insofar as they are viable, are straightforwardly compatible with the positing of chances to explain and predict reliable statistics. But Sober's 'no-theory theory' is especially well suited to our interests as he posits probabilities without further analysis (one might think of Sober's view as a metaphysically lightweight propensity theory):

> In view of the failures of these [Humean, propensity, etc.] interpretations, my preference is to adopt a no-theory theory of probability, which asserts that objective probability is not reducible to anything else. Frequencies provide evidence about the values of probabilities, and probabilities make (probabilistic) predictions about frequencies, but probabilities don't reduce to frequencies
>
> [Sober (2010, p. 149)]

The 'no-theory theory' is attractive insofar as it allows that one may be confident that probabilities are objective without knowledge of what underwrites them; see also Fernandes (2023). But the "not reducible" needn't imply that such probabilities cannot be explained as set out above in terms of the emergence of robust and reliable statistical patterns. Likewise Hoefer (2019)'s analysis develops a Humean acccount of probability that sources these in reliable non-fundamental statistics and may provide an alternative analysis of the probabilities in the chaotic systems discussed previously.

3 Emergent Probabilities Are Objective

Now if such probabilities are countenanced, we may ask whether they are objective – to paraphrase Albert (2000) – the milk mixing into my coffee cares not a jot about my epistemic states! Objective probabilities have (at least) the following features: knowledge of the sequence until time t does not licence determinate prediction of the continuation of the sequence at $t+1$, knowledge of objective probabilities licences inferences about the relative frequencies, and the relative frequencies constrain the objective probabilities.

But why should we think of probabilities as objective? The label 'objective' in discussions of probability is best contrasted with subjective, while epistemic is contrasted with ontic, and will be discussed further below.

Therefore, a helpful guide to whether or not the emergent probabilities discussed above are objective is the meaningfulness of inter-subjective disagreement about the probability distributions. If all well-informed observers will assign the same distribution then we have good reason to suppose that our probabilities are objective. Physical mechanisms which secure inter-subjective agreement on the probability distribution will be termed 'objectification mechanisms'. The most recognisable form of objectification mechanisms underpin games of chance; so dice, roulette wheels, coin flips, and similar devices are such that a huge range of initial conditions will lead to a uniform distribution over the possible outcomes.[5]

Myrvold (2021) develops this analysis in detail starting with a device that, through its deterministic evolution, establishes convergence to the same distribution over coarse-grained variables, for almost any starting distribution (with some exceptions that we may regard as fine-tuned). Myrvold goes on to consider how the dynamics of statistical mechanical systems enact an analogous form of objectification.[6]

One difference between Myrvold's analysis and that developed here is that he insists that the probabilities are to be considered 'epistemic chances' rather than objective and ontic probabilities. The reason is that he believes that the initial distribution may be understood as representing our ignorance over the precise initial state. By contrast I take inspiration from Ismael (n.d.) and Strevens (2011) and insist that the initial distributions stem from noise and/or quantum probabilities, and as such any reference to credences may be discarded.

What's crucial for the claim of objectivity is that for a wide range of initial distributions we have convergent and, thus, intersubjectively agreed upon distributions over the coarse-grained final variables. This is explained by the attractor dynamics. As will be discussed further below, a focus on objectification mechanisms provides an alternative to the literature's attention to initial conditions. A probability distribution over initial conditions is rather hard to interpret – it's not at all clear why such a distribution should have any connection to what is in fact observed. On the

---

[5] de Canson (2022) claims that the method of arbitrary functions is not the source of the objectivity of such probabilities. Insofar as she allows (§5) that objectivity is rather relatable to coarse-graining functions more generally then we agree. But it's also worth noting that I advocate a slightly different sense of objectivity to those she considers: robust statistics are objective in the sense that observers with a range of different information about the initial conditions/distributions should agree on the statistics.

[6] For further discussion of Myrvold's book see Robertson and Franklin (2024).

other hand objectification mechanisms deliver reliable and regular statistics. These mechanisms objectify the distributions – more or less however you start, you end up with the same results.

The claim is that objectivity is achieved via real-world processes that guarantee the convergence of statistics. Thus it's not about our ignorance and it is able to support inter-subjective agreement. Not all systems exhibit objective probabilities, but insofar as there is an objectification mechanism that leads to regular statistics we have good reasons to posit objective probabilities. The objectification mechanisms – such as the attractor dynamics – tell us which are the right abstractions to describe a system, or in other words, which is the broad class of partitions with respect to which there will be regular statistics.

4 Emergent Probabilities are Ontic

A further question remains: are these objective probabilities properly thought of as epistemic? Insofar as the systems described have fundamental deterministic dynamics there's a sense in which one could come to know enough about the initial conditions such that the later condition is predictable without recourse to probabilities. But one needs to specify initial conditions arbitrarily precisely given the exponential divergence of SDIC systems: the dynamics are non-linear and are not known to have analytic solutions; and the system has quantum inputs and/or noisy perturbations which further undermine any attempt at deterministic prediction.

In this section I will outline three routes to ontic probabilities: first via quantum mechanics, second via considerations of explanatory power, and third (in close relation to the second) I will develop in detail my preferred emergentist response.

First, if the initial conditions for the chaotic evolution are determined via a quantum dynamical process, and the dynamical evolution is one which is in-principle derivable from quantum physics, then the probabilities discussed here just are quantum probabilities. Following Wallace (2020), if one views quantum theory as a framework theory then this argument is rendered more plausible and so we might accept that the medium-term weather probabilities discussed here just are quantum probabilities. I will not rely on this line of argument alone for two reasons. First, many are sceptical that quantum probabilities are ontic, this is controversial on many interpretations of quantum mechanics and especially on Everettian approaches. Second, in §2.3 I discussed the source of the distribution over initial conditions in the model – the basis for moving from an exact specification of a single initial condition to a (narrow) distribution over initial conditions – and established that even putting quantum mechanics aside any real-world system will be the subject of continual buffeting by external factors that we may group under the label 'noise'. If that's the case then not all such probabilities are solely quantum; on the other hand quantum mechanics as a theory with very broad scope may still be capable of bringing all such sources of noise under a wider scope.[7] Importantly, these considerations are subject to doubt concerning both quantum physics imperialism – the view that every relevant system could be brought under the scope of quantum physics – and the nature of quantum probabilities. Given that doubt it's certainly worth developing additional routes to onticness.

The second route is far more general and involves broadly metaphysical considerations.[8] Bird (2018) argues that we should be realist about properties that are explanatory and the result of selective evolutionary processes, where the latter criterion establishes their multiple realisability. An analogous argument can be defended in this context, for the dynamics of the attractor also selects particular distributions and the probabilities explain the observed frequencies of types of outcome. In this context, too, we have multiple realisability since different starting points and distributions will lead to the same statistics. The relevant contention is that irrespective of whether there's some sense in which probabilities discussed here are predictively dispensable were one to know the exact initial conditions and had one the capacity to compute the future evolution of such systems, the probabilities should be accepted as real because science and scientific explanation could not do without them.

The third route is closely related but builds on more general ontological criteria developed elsewhere to argue that these probabilities are ontologically emergent. The thought is that featuring in successful explanations is a necessary criterion for inclusion in the scientific realist's ontology, but to avoid arbitrary duplication of kinds we should have more restrictive sufficient criteria. This account of emergence builds on the real patterns con-

---

[7] Thanks to David Wallace for raising this objection and suggesting pseudo random number generators as a reason to think that there at least some regular statistics in the world whose source is not quantum probabilities.

[8] Thanks to Sam Kimpton-Nye for pushing me on this.

cept introduced by Dennett (1991) and extended by Franklin and Robertson (2024), Ladyman and Ross (2007), Ross (2000), and Wallace (2021). Given that we don't have a fundamental theory of physics, the inclination of some metaphysicians to restrict ontological commitments to whatever is posited by such a theory would leave us with an empty ontology.[9]

While many are inclined to grant, at least, that there are philosophers, electrons, and some other things too, non-fundamental probabilities are often not extended the same courtesy. The probabilities posited by dynamical collapse theories, qua posits of a putatively fundamental theory are regarded as ontic, but probabilities of emergent theories are dismissed as epistemic. Some of this suspicion has to do with worries over probabilities more generally, and I discussed that briefly in §2.5. My target here is those who are willing to accept that fundamental probabilities, if there are any, are ontic, and yet are wary of regarding non-fundamental probabilities in a similar light. My claim is that, just as it's wrong to think of the inclusion of tigers in our ontology as anthropocentric, even though they might in some sense be predictively redundant were we to be able to detect and track their internal movements and cell interactions, it's likewise a mistake to think that just because some fictional keen-sighted alien might be able to do better than some mid-term weather forecast, that the weather probability is better thought of as epistemic than ontic. To defend this analogy I'll outline an account of emergence and show that just the same analysis which legitimates non-fundamental ontology can also legitimate non-fundamental ontic probability.

According to Franklin and Robertson (2024) an entity is emergent if and only if it is involved in dependencies that are novel and screen off lower-level details. Screening off involves the combination of unconditional relevance with conditional irrelevance.

Unconditional relevance: conditional on a particular lower-level description (LLD), the probability of the macro-description A obtaining increases: $P(A|LLD) > P(A)$. Under certain circumstances[10], $P(A|LLD) = 1$.

Conditional irrelevance: $P(A|B\&LLD) \approx P(A|B) = x$ where $0 \leq x \leq 1$. Another way of showing that some lower-level feature is irrelevant, is by comparing two LLDs which differ with respect to that feature:

---

[9] A related point is made in Schaffer (2004).

[10] If the microdynamics take all the members of the supervenience basis of B to members of the supervenience basis of A.

$P(A|B\&LLD_1) = P(A|B\&LLD_2)$. Following Wallace (2019) an assumption of 'Naturalness' may legitimate ruling out those initial microstates that would undermine screening off, and thus restore the full equality. In mathematised sciences, Franklin and Robertson (2024) argue that an entity is novel if it features in macrodependencies with distinct functional form from the corresponding microdependencies: consider, for example, the difference between the equations of quantum and classical physics.

We can spell this out with a simple example: the positions/momenta of the particles that constitute a bouncy ball at t are *unconditionally relevant* to the height of the bounce at $t + 1$. Conditionalising on the height/spin/macroproperties of the ball at t, the particles' positions are *conditionally irrelevant*. And the macrodynamics have a distinct functional form. Therefore the lower-level details are screened off and the bouncy ball is emergent from its more fundamental parts.

To apply this analysis to the current case-study: the lower-level details – the microstate of the weather system and its underlying evolution – are *unconditionally relevant* to weather prediction. That is, were we to know the full microstate exactly and the laws that govern the system then we may be able to predict its future state either deterministically or stochastically. However, conditional upon the dynamics exhibiting an attractor and approximately instantiating the conditions for mixing, then the lower-level distribution will be approximately screened off from the statistics for final outcomes. That's because the attractor and the mixing together guarantee regular and reliable statistics with respect to the coarse-grained variables, and predictions cannot be improved by greater precision in the initial conditions due to the exponential divergence corresponding to SDIC, and the fact that real-world systems are subject both to noise and to quantum mechanical effects. The coarse-grained variables at the higher level also employ different kinds and exhibit novel regularities relative to the underlying description. Therefore the medium-term weather probabilities are emergent and count as ontic.

The screening off claim is expressed clearly by Werndl (2009, p. 215): "[h]ence, mixing means that for predicting an arbitrary event at an arbitrary level of precision $\epsilon > 0$, any sufficiently past event is approximately probabilistically irrelevant."

While the specific claims here are premissed on the details of chaos theory, there's good reason to think that these results will generalise. In order to arrive at the conditional irrelevance what's required is some kind of convergence of distributions, and this is provided by many of the probabilistic/chancy systems we encounter in everyday life. In general we may refer to these as objectification mechanisms that are relatively generic: dynamical effects (effectively) screen off the initial conditions from the macrovariables of interest and regular and reliable statistics are observed. These probabilities are objective in the sense that they are subject to inter-personal agreement and they explain and predict objective statistics. And they are ontic in the sense that they are emergent – they feature in novel and screening off dependencies.

One might worry: Is the coarse-graining that plays a role in the above analysis too epistemic? In instances of emergence much work goes into identifying the *right* higher-level variables, though in general a wide range of higher-level variables may instantiate robust statistics. It's relative to the coarse-grained variables that we have screening off of lower-level details. That's what objectification gives us: a privileged set of variables, with respect to which we have regular higher-level statistics. So these probabilities deserve the 'ontic' label as much as other emergent kinds. Bacciagaluppi (2020, pp. 31–32) acknowledges the pragmatic element to the ontic vs. epistemic distinction: ."If we can extend or restrict at will which propositions we assume to be knowable in principle, then any probability can be alternatively seen as epistemic or as ontic, and there is no substantive difference between the two." While Bacciagaluppi goes on to temper this claim somewhat, I agree that the distinction is to some extent pragmatic. However, I contend that in cases that fit the account of emergence defended in Franklin and Robertson (2024) we have an additional reason to accept the 'ontic' label that does not depend on a criterion of knowability. To describe all weather probabilities as epistemic would fail to recognise the commonality with other instances of emergence.

This exemplifies a paradigmatic feature of emergent systems, highlighted in Knox (2016). The statistics exhibited by chaotic systems after a certain time are only relative to a particular set of coarse-grained variables. Different variables will lead to different statistics, and many choices of variables will lead to no robust statistics at all. It's a dynamical phenomenon – in this case related to the attractor – that such statistics are to be found relative to a particular choice of variables. However, this does not undermine the objectivity claim. It's a consequence of the structure of such systems that robust statistics are exhibited, but they aren't to be found at all levels or for all choices of system descriptions. The fact that they can be identified in some clearly described circumstances is sufficient to claim that they are really out there.

This implicates another feature in common with emergent ontology more generally: it's not meaningful to ask 'what is there?' – in this context 'what is the probability?' – without specifying a level, where the specification of a reference class will in general suffice to pick out a level. This tells us that entities and probabilities are essentially associated, respectively, with types and frequencies. This provides a further reason to be sceptical about initial conditions probabilities, as the lack of a sequence or reference class underdetermines the probability involved.

Overall, as evident from consideration of weather attribution and its link to climate change, viewing the probabilities of weather systems as both ontic and objective makes clear that changes to such probabilities is the result of physical processes, and that such changes are therefore, in principle, the subject of moral and legal responsibility. By contrast epistemic chances may be changed by a mere update in information available to an agent.

5 Initial Conditions Accounts

There is of course an extensive literature that discusses the origin of probabilities in statistical physics, and some may find aspects of the above discussion redundant as a consequence. What is being added to accounts offered by Albert (2000) and Loewer (2023), Frigg and Hoefer (2019), Wallace (2011), and others of the source of non-fundamental probabilities in those contexts? In outline this account agrees with much of the literature. The source of the probabilities does rely on a distribution over initial conditions (though there is perhaps more commonality with Price (1997) and Frisch (2023)). And there is an especial link to Wallace's suggestion that all probabilities are quantum – this project may be a distinct vindication of that view. However, I follow Strevens and Myrvold in their emphasis: it's the convergence results that matter more than the initial conditions.

One of the best known accounts of the source of non-fundamental probabilities is provided by Albert and Loewer. This has been labelled 'Statistical Mechanical Imperialism' (see Weslake (2014)). Barry Loewer describing joint work with David Albert sets out the 'Mentaculus' as starting with three elements: 1, spacetime and the 'dynamical laws', 2, the past hypothesis around the time of the big bang M(0), 3, the statistical postulate that "specifies a uniform probability distribution (specified by the standard Liouville measure) over the physically possible microstates that realize M(0)" Loewer (2023, p. 14)

> The 'Mentaculus' is an appropriate name for this theory because the package of the three ingredients above determines a probability density over the set of physically possible trajectories of microstates emanating from M(0) ... i.e. a probability map of the world

I'm happy to endorse Albert and Loewer's account to the following extent: some input probability distribution is required, and evolution via the laws will take us from this input distribution to the distribution over any events, delivering the non-fundamental probabilities. As discussed above, the input probability distributions may be sourced in quantum probabilities (ultimately via e.g. the Bunch-Davies vacuum, see Wallace (2023)), or in noise/interference from external systems, with some non-correlation postulate (see Frisch (2023)). But accounts that focus on the initial distribution and assume that it's sufficient just to advertise evolution via "the dynamical laws" fails to pay sufficient attention to the features of such laws which deliver the non-fundamental probabilities.

The source of probability cannot be the initial distribution alone, for every token system will have a different actual starting point, and the existence of other possible starting points is logically irrelevant to the details of our system. The positing of single case probabilities does not explain what we in fact observe. Thus the source of objectivity must rely on the existence of attractors – the details of the dynamics – and the relation between these and the probability distributions rely on coarse graining operations that can describe our system in such a way that it exhibits regular and reliable statistics with respect to the new coarse grajned variables.

It's only by considering such objectification in addition to the initial conditions that Ismael's challenge can be addressed:

> In concrete terms, the principle to be derived to generate thermodynamic behavior is that there is a high statistical probability that the microstates of local, approximately adiabatically isolated subsystems of the world are normal, or – to put

> it another way – that abnormal microstates are so exceedingly rare under natural conditions that we should be shocked to see them, i.e., that when we sample such systems, we never find one arising naturally whose microstate is among those very special ones that produce anti- thermodynamic behavior. ... we have a very incomplete understanding of the links that are supposed to bridge the gap between these global postulates and the phenomenological regularities embodied in thermodynamic generalizations. And as before, once it is filled, it would seem that we could dispense with the global SP [statistical postulate], since it is the local one that is needed to recover thermodynamic generalizations
>
> [Ismael (n.d., pp. 5–6)]

Similarly, Earman claims: "the Past Hypothesis, even if true, does not explain why ordinary thermodynamics works as well as it does for the types of systems of interest to us, and the widespread celebration of this hypothesis has been counter-productive in obscuring the hard work that still needs to be done to secure a satisfactory explanation." Earman (2006, p. 420)

Ismael's worry against Albert and Loewer's account is that, even were we to assume that our universe started with a typical initial condition – one that is rendered probable by the uniform distribution over the possible initial microstates – that assumption is not sufficient to guarantee that most local systems will be in any way typical or that the observed frequencies are likely to match those of any of our probabilistic theories. In fact the Albert/Loewer package of assumptions posits incredibly weak constraints on the behaviour of any actual subsystem. What we in fact would like is some reasonable expectation that any given subsystem is typical in order to have some expectation that the local assignment of probabilities to that subsystem will match those posited by the relevant theory. The result of all this is that the initial probabilities accounts are woefully inadequate if one is after an account of how the statistics we observe emerge from our more fundamental theories. Although everything I say is in principle compatible with their account, their view is not sufficient to do the advertised work.

Frigg and Hoefer (2019, p. 189) develop a related account: building on work by Lavis, they also find the source of statistical mechanical probabilities in distributions over initial conditions: "whether or not a system's motion is ergodic depends on the initial condition: some initial conditions lie on trajectories that are ergodic, while others don't. This realization is the clue to introducing probabilities. Consider an arbitrary subset $C \subseteq \Gamma_p$. We may postulate that the probability that the initial condition X lies within C at time t_0 is $p(C) = \frac{\mu(C)}{\mu(\Gamma_p)}$". If we take E to be the set of ergodic trajectories then, if $p(E)$ is high, we are taken to have justified the expectations of thermodynamics. This is further justified by Frigg and Werndl (2011).

While Frigg and Hoefer make significant progress in explaining the observed statistics by advertising the ergodicity condition (closely related to the mixing condition discussed above), they too rely on an underdeveloped appeal to initial condition probabilities, and it's at least unclear that their account is generalisable to probabilities in physics in general, as their title suggests.

By contrast, Wallace (2015) and Myrvold (2021) do provide something akin to objectification mechanisms.[11] Both focus on how an evolution towards an attractor distribution relies on coarse graining to end up in the equilibrium state. As such, they have an account that depends on common features of various kinds of dynamical systems rather than just a constraint on the global initial conditions. Their accounts provide examples that are akin to that discussed above for chaotic systems. Wallace's grander claims that all the non-fundamental probabilities are ultimately derived from those of quantum mechanics may be also substantiated by the proposals here, for it shows that if we start with quantum probabilities, either globally or locally for an individual systems, the dynamics will lead to the convergence upon regular and reliable statistics with respect to the right choice of higher-level variables.

6 Conclusion

Objective statistics are widespread in statistical mechanics, in weather systems, in games of chance, and in many other fields. I've argued that the probabilities which predict and explain such statistics gain their objectivity through the coupling of an initial probability distribution with relevant features of the dynamics – chiefly an attractor and the approximate satisfaction of the mixing conditions, which conduce to a certain choice of higher-level variables. The initial distribution may be sourced in either external

---

[11] Myrvold's dynamical condition is weak mixing, Wallace's is a bit more complicated – see discussion in Robertson (2020) for more detail.

random noise or quantum/more fundamental probabilities. The resultant higher-level probabilities satisfy the constraints of an account of emergence developed elsewhere and as such should be regarded as ontic.

The case of chaos was considered in order to provide an explicit demonstration of these arguments but they ought to generalise to probability distributions over which there is inter-subjective agreement due to dynamical objectification mechanisms. While much work has gone into considering the source of statistical mechanical probabilities, relatively less has gone into the consideration of the emergence of probabilities more generally. I have argued that there are many sources of such probabilities – and many distinct objectification mechanisms. Once we have such mechanisms, we may regard such probabilities as emergent, and, therefore, as ontic and objective.

One further reason for developing these arguments in the context of chaos theory is because weather is chaotic and this will therefore have implications for the following issue:

In the last few years climate models have been used not only to project features of the global climate based on different greenhouse gas emissions scenarios but also to link such emissions to increased frequency of extreme weather events. The studies asserting this latter connection are the subject of numerous news reports and some court cases, where they have been used to substantiate claims that significant emitters of greenhouse gases are partially causally responsible for particular floods or droughts(e.g.Li and Otto (2022), see Winsberg, Oreskes, and Lloyd (2020) for recent philosophical analysis).

Such claims are based on the comparison of two probabilities: the probability for the extreme weather event to occur given current levels of greenhouse gases in the atmosphere, and the probability for the same event based on a counterfactual model of much lower emissions (historic conditions are often used as a proxy for the latter). The change in probability is thus interpreted as evidence of a causal link. This prompts a puzzle: the assumption in the small literature on the nature of probabilities in climate science is that such probabilities are best understood as personal, subjective probabilities – known as 'credences'.[12] This follows the IPCC guidance where probabilities are taken to quantify scientific uncertainty, see Mas-

---

[12] Though see Winsberg (2018, Ch.6) for the observation that weather probabilities are objective by contrast with climate probabilities.

trandrea et al. (2010). And yet an increase in the credence of an event does not justify a causal attribution. A scientist's coming to know more facts about some target system does not make any difference to what happens in that target system – mere changes to scientists' credence concerning extreme weather events without a corresponding change in the objective chances of such events do not imply that the frequency of such events has changed.

The standard philosophical analysis that links causation to probability claims that cause C causes effect E if C raises the chance of E's occurrence (Hitchcock (1997)). However, raising the credence in E's occurrence is irrelevant. Relative change in credences would be of no consequence to causal attribution. Thus, in order to play the advertised role and enable the kinds of causal responsibility attributions, we need to recognise the probabilities as objective chances. This would be to establish that, despite the probabilities for these events' being the output of climate models, they are ontic and objective. The hope, therefore, is that the work in this paper allows for the claims made in weather attribution studies to be substantiated, and should as a consequence bolster the legal arguments that high emitters are at least partially causally responsible for extreme weather events.

Acknowledgements

Many thanks to Lucy Mason, David Papineau, and Katie Robertson, for discussion of many of these ideas, and thanks to Donald Franklin, Wayne Myrvold, Brett Nathaniel Park, the audiences at the Stirling workshop on Statistical Mechanics and the Arrow of Time, the PSA 2024, Foundations of Physics online reading group, and the KCL staff seminar for helpful feedback and comments.

References

Albert, David Z. (2000). *Time and Chance*. Harvard University Press.

Bacciagaluppi, Guido (2020). "Unscrambling subjective and epistemic probabilities". In: *Quantum, Probability, Logic: The Work and Influence of Itamar Pitowsky*, pp. 49–89.

Batterman, Robert W. (2021). *A Middle Way*. OUP.

Beebee, Helen and David Papineau (1997). “Probability as a Guide to Life”. In: *The Journal of Philosophy* 94.5, pp. 217–243.

Bird, Alexander (June 2018). “I—Fundamental Powers, Evolved Powers, and Mental Powers”. In: *Aristotelian Society Supplementary Volume* 92.1, pp. 247–275. DOI: `10.1093/arisup/aky006`.

Buizza, Roberto (2002 2002). *Chaos and Weather Prediction*. eng.

de Canson, Chloé (2022). “Objectivity and the method of arbitrary functions”. In: *The British Journal for the Philosophy of Science*.

Dennett, Daniel C. (1991). “Real patterns”. In: *The Journal of Philosophy*, pp. 27–51.

Earman, John (2006). “The “past hypothesis”: Not even false”. In: *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 37.3, pp. 399–430.

Elliott, Katrina (2021). “Where Are the Chances?” In: *Synthese* 199.3-4, pp. 6761–6783.

Emery, Nina (2015). “Chance, possibility, and explanation”. In: *The British Journal for the Philosophy of Science*.

Fernandes, Alison (2023). “Naturalism, Functionalism and Chance: Not a Best Fit for the Humean”. In: *Humean Laws for Human Agents*. Ed. by Michael Hicks, Siegrfied Jaag, and Christian Loew. Oxford University Press.

Franklin, Alexander (2023). “Incoherent? No, Just Decoherent: How Quantum Many Worlds Emerge”. In: *Philosophy of Science*. DOI: `10.1017/psa.2023.155`. Forthcoming.

Franklin, Alexander and Katie Robertson (2024). *Emerging into the Rainforest: Emergence and Special Science Ontology*. https://philsci-archive.pitt.edu/24132/. Forthcoming in European Journal of Philosophy of Science.

Frigg, Roman and Carl Hoefer (2019). “Chance in the world: A Humean guide to objective chance”. In: Oxford University Press. Chap. Humean Chance in Physics.

Frigg, Roman and Charlotte Werndl (2011). “Explaining thermodynamic-like behavior in terms of epsilon-ergodicity”. In: *Philosophy of Science* 78.4, pp. 628–652.

Frisch, Mathias (2023). “Causes, Randomness, and the Past Hypothesis”. In: *The Probability Map of the Universe: Essays on David Albert?s* Time and Chance. Ed. by Barry Loewer, Brad Weslake, and Eric Winsberg. Cambridge MA: Harvard University Press.

Glynn, Luke (2010). “Deterministic chance”. In: *The British Journal for the Philosophy of Science*.

Grebogi, Celso, Edward Ott, and James A Yorke (1987). "Chaos, strange attractors, and fractal basin boundaries in nonlinear dynamics". In: *Science* 238.4827, pp. 632–638.

Habib, Salman, Kosuke Shizume, and Wojciech Hubert Zurek (1998). "Decoherence, chaos, and the correspondence principle". In: *Physical review letters* 80.20, p. 4361.

Hitchcock, Christopher (1997). "Probabilistic causation". In: *Stanford Encyclopedia of Philosophy*.

Hoefer, Carl (2019). *Chance in the world: A Humean guide to objective chance*. Oxford University Press.

Ismael, Jenann (n.d.). *Do Statistical Mechanical Probabilities Need Quantum Shuffling? Albert's Boltzmannian Story and GRW*.

Kellert, Stephen H (1993). *In the wake of chaos: Unpredictable order in dynamical systems*. University of Chicago press.

Knox, Eleanor (2016). "Abstraction and its Limits: Finding Space For Novel Explanation". In: *Noûs* 50.1, pp. 41–60.

Ladyman, James and Don Ross (2007). *Every Thing Must Go: Metaphysics Naturalized*. Oxford University Press. With David Spurrett and John Collier.

Li, Sihan and Friederike EL Otto (2022). "The role of human-induced climate change in heavy rainfall events such as the one associated with Typhoon Hagibis". In: *Climatic Change* 172.1, p. 7.

List, Christian (2018). "Levels: Descriptive, Explanatory, and Ontological". In: *Nôus*, pp. 1–32.

Loewer, Barry (2023). "The Mentaculus: A Probability Map of the Universe". In: *The Probability Map of the Universe: Essays on David Albert?s* Time and Chance. Ed. by Barry Loewer, Brad Weslake, and Eric Winsberg. Cambridge MA: Harvard University Press.

Mastrandrea, Michael D et al. (2010). "Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties". In.

May, Robert M and George F Oster (1976). "Bifurcations and dynamic complexity in simple ecological models". In: *The American Naturalist* 110.974, pp. 573–599.

Myrvold, Wayne C (2021). *Beyond chance and credence: A theory of hybrid probabilities*. Oxford University Press, USA.

Palmer, Tim N. (2019). "Stochastic weather and climate models". In: *Nature Reviews Physics* 1.7, pp. 463–471.

Palmer, Tim N., A Döring, and G Seregin (2014). "The real butterfly effect". In: *Nonlinearity* 27.9, R123.

Price, Huw (1997). *Time's Arrow and Archimedes' Point: New Directions for the Physics of Time*. Oxford University Press.

Robertson, Katie (2020). "Asymmetry, Abstraction, and Autonomy: Justifying Coarse-Graining in Statistical Mechanics". In: *The British Journal for the Philosophy of Science* 71.2, pp. 547–579. DOI: `10.1093/bjps/axy020`.

Robertson, Katie and Alexander Franklin (2024). "Objective Credences, Epistemic Chances, and Explanations of Time Asymmetry: Review of Myrvold's 'Beyond Chance and Credence'". In: *Foundations of Physics*.

Ross, Don (2000). "Rainforest realism: A Dennettian theory of existence". In: *Dennett's Philosophy: A Comprehensive Assessment*. Ed. by Don Ross, Andrew Brook, and David Thompson. MIT Press.

Schaffer, Jonathan (2004). "Two Conceptions of Sparse Properties". In: *Pacific Philosophical Quarterly* 85.1, pp. 92–102. DOI: `https://doi.org/10.1111/j.1468-0114.2004.00189.x`.

Shen, Bo-Wen et al. (2021). "Is Weather Chaotic?: Coexistence of Chaos and Order within a Generalized Lorenz Model". In: *Bulletin of the American Meteorological Society* 102.1, E148–E158. DOI: `10.1175/BAMS-D-19-0165.1`.

Slingo, Julia and Tim N. Palmer (2011). "Uncertainty in weather and climate prediction". In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369.1956, pp. 4751–4767.

Smith, Peter (1998). *Explaining Chaos*. Cambridge University Press.

Sober, Elliott (2010). "Evolutionary theory and the reality of macro-probabilities". In: *The Place of Probability in Science*. Springer.

Strevens, Michael (2011). "Probability out of determinism". In: *Probabilities in physics* 146.

Wallace, David (Nov. 2011). "The Logic of the Past Hypothesis". In.

— (2012). *The Emergent Multiverse: Quantum Theory according to the Everett Interpretation*. Oxford University Press.

— (2015). "The quantitative content of statistical mechanics". In: *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 52, pp. 285–293.

— (2019). "Naturalness and emergence". In: *The Monist* 102.4, pp. 499–524.

— (2020). "On the Plurality of Quantum Theories: Quantum Theory as a Framework, and its Implications for the Quantum Measurement Problem". In: *Scientific Realism and the Quantum*. Ed. by Steven French and Juha Saatsi. Oxford University Press.

— (Dec. 2021). *Stating structural realism: mathematics-first approaches to physics and metaphysics*.

— (2023). "The local quantum vacuum as the Past Hypothesis". In.

Werndl, Charlotte (2009). "What are the new implications of chaos for unpredictability?" In: *The British Journal for the Philosophy of Science*.

Weslake, Brad (2014). "Statistical Mechanical Imperialism". In: *Chance and Temporal Asymmetry*. Ed. by Alastair Wilson. Oxford University Press, pp. 241–257.

Wilson, Alastair and Toby Handfield (2014). "Chance and Context". In: *Chance and Temporal Asymmetry*. Oxford University Press, pp. 19–44.

Winsberg, Eric (2018). *Philosophy and climate science*. Cambridge University Press.

Winsberg, Eric, Naomi Oreskes, and Elisabeth Lloyd (2020). "Severe weather event attribution: Why values won't go away". In: *Studies in History and Philosophy of Science Part A* 84, pp. 142–149.

Zhang, Fuqing et al. (2019). "What Is the Predictability Limit of Midlatitude Weather?" In: *Journal of the Atmospheric Sciences* 76.4, pp. 1077–1091. DOI: `10.1175/JAS-D-18-0269.1`. URL: `https://journals.ametsoc.org/view/journals/atsc/76/4/jas-d-18-0269.1.xml`.

Zuchowski, Lena C (2017). *A philosophical analysis of chaos theory*. Springer.