ESI Erwin Schrödinger International Institute for Mathematics and Physics

universität wien

DVR 0065528

Concepts of Probability in the Sciences

October 29 – 30, 2018

Abstracts

What is quantum in quantum randomness?

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It is often said that quantum and classical randomness are of different nature, the former being ontological and the latter epistemological. However, so far the question of "What is quantum in quantum randomness", i.e. what is the impact of quantization and discreteness on the nature of randomness, remains to answer. In this talk I will first explicit the differences between quantum and classical randomness within a recently proposed ontology for quantum mechanics based on contextual objectivity. In this view, quantum randomness is the result of contextuality and quantization. I will show that this approach strongly impacts the purposes of quantum theory as well as its areas of application. In particular, it challenges current programs inspired by classical reductionism, aiming at the emergence of the classical world from a large number of quantum systems.

In a second part, I will analyze quantum physics and thermodynamics as theories of randomness, unveiling their mutual influences. I will finally consider new technological applications of quantum randomness opened in the emerging field of quantum thermodynamics.

Probabilistic Explanations and the Derivation of Macroscopic Laws

Jean Bricmont
Université catholique de Louvain

We will discuss the link between scientic explanations and probabilities, especially in relationship with statistical mechanics and the derivation of macroscopic laws from microscopic ones.

Wigner's friend as a rational agent

Časlav Brukner
University of Vienna

In 1961 the physicist Eugene Wigner proposed the "Wigner's friend" thought experiment in which an observer, Wigner, observes another observer, Friend, who performs a quantum measurement on a physical system. I will give evidences that the probabilistic statements of Wigner and Wigner's Friend cannot fit into a single (observer-independent) theoretical framework, and are to be understood as relational in the sense that their determinacy is relative to an observer.

What Is Generic and What Is Special about the Universe?

Erik Curiel
Munich Center for Mathematical Philosophy

Some of the deepest questions in cosmology concern what features of our universe are generic and what are special. Was the highly homogeneous state of the very early universe special in some sense (i.e., unlikely, and so seemingly requiring explanation)? Do spacetimes such as ours generically possess singularities (i.e., are singularities highly probable)? To attempt to formulate such questions precisely and then address them requires probabilistic concepts and reasoning. Because of the peculiar and complex nature of the candidates to serve as probability spaces involved, standard forms of probabilistic concepts and reasoning do not apply. I discuss the problems such questions pose, and consider some possibilities for addressing them. I conclude by discussing the consequences of those problems for how we should assess the strength of standard forms of argument in sciences such as cosmology that would attempt to reason probabilistically about unique and large entities such as the universe as a whole.

Inferring statistical ensembles from experiment and simulation

Gerhard Hummer
Max Planck Institute of Biophysics
Frankfurt am Main

Statistical mechanics describes the thermal disorder of molecular systems in terms of statistical ensembles, such as the Boltzmann distribution $p_0(\mathbf{r}) \propto \exp[-\beta H_0(\mathbf{r})]$ of classical mechanics. Given an approximate classical or quantum mechanical energy function $H_0(\mathbf{r})$, molecular simulations produce weighted configurations that jointly represent the statistical ensemble. How should one adapt the weights of these configurations, or more generally the underlying "Boltzmann distribution" $p_0(\mathbf{r})$, when new experimental information emerges?

I address this problem of "ensemble refinement" in a (somewhat unusual) Bayesian framework. Bayesian formulations are widely used to update the probability distribution of certain parameters of a model in light of new data. Here, the "parameter" is the distribution $p(\mathbf{r})$ describing the ensemble. Both the Bayesian prior and posterior distributions are thus functionals, connected by a likelihood functional that quantifies the deviations between the predicted experimental observables according to $p_0(\mathbf{r})$ and the experimental observations.

Variational maximization of the posterior functional produces an "optimal" ensemble weight function $p(\mathbf{r})$. Formally, $p(\mathbf{r})$ adopts the form of the Gull-Daniel maximum-entropy formulation. However, the interpretation is different. In particular, a tunable Lagrange multiplier here becomes a combination of statistical error of the measurements and a parameter ⍰ expressing our confidence in $p_0(\mathbf{r})$ [or $H_0(\mathbf{r})$]. Practically, for a finite sample with discrete weights $w_i^0 = p_0(\mathbf{r}_i)$, the optimal weights can be determined by minimizing an effective free energy, in which the chi-squared term adopts the form of the energy, and the entropy term adopts the Kullback-Leibler form.

The optimal ensemble weight function $p(\mathbf{r})$ found in this way is a trade-off between the reference ensemble, $p_0(\mathbf{r})$, and the new information provided in the form of observations and their errors. One can interpret the optimal ensemble weight in terms of a modified energy function $H(\mathbf{r})$, in which generalized forces acting on observables appear as additional terms. These generalized forces have a mechanical interpretation: for the optimal ensemble, the "mean force" trying to restore the reference distribution $p_0(\mathbf{r})$ is exactly balanced by the "mean force" trying to fit the data, as determined by the gradient of the log-likelihood.

In summary, the integration of experimental data and molecular simulations using a Bayesian formulation leads to a distribution of probability distributions. Its extremum adopts a maximum-entropy form, albeit with a transparent interpretation of errors in the experiments and in the calculation of experimental observables. Overall, one arrives at a new energy function $H(\mathbf{r})$ that modifies the original $H_0(\mathbf{r})$ to account for the experimental data and their uncertainties. This formulation establishes a firm foundation for ensemble refinement with applications, e.g., in integrative structural biology.

Understanding Entropy without Probability

Elliott Lieb
Princeton University

Probabilistic models can be very effective for calculating entropy. Examples include the awesome agreement between Pauling's model of the residual entropy of ice and the careful experiment of Giauque and Stout. Nevertheless, it is important to realize that models are not needed to understand the definition and properties of thermodynamic entropy, especially the remarkable fact of 'additivity', which relates the entropies of totally unrelated systems. A fundamental theory of entropy as an indicator of the possibility of adiabatic processes was provided by Jakob Yngvason and myself in the last century and will be reviewed briefly.

QBism and normative probability in quantum mechanics

Rüdiger Schack
University of London

What course of action should I take? This is the question that decision theory is designed to answer. An agent's rational decision-making is constrained by the rules of the probability calculus which thus plays a normative role in decision theory. According to QBism, the quantum formalism is a tool that any agent can use to answer the very same question: What course of action should I take? In the QBist approach, probabilities in quantum mechanics guide an agent's decision-making, and the Born rule functions as a further normative constraint on the agent's probability assignments, in addition to the constraints imposed by probability theory. In this talk I give a simple introduction to the decision-theoretic approach to probability and explain how quantum mechanics itself provides compelling arguments for the QBist view.

Chance and Randomness in Evolutionary Processes

Peter Schuster
University of Vienna

Evolution is in the core of biological thinking. Evolutionary processes are inevitably dealing with small numbers of individuals, since every mutant starts from a single copy. Reproduction is just a complex form of autocatalysis, which can be studied in great detail as an elementary chemical reaction. In the lecture we distinguish four different sources of randomness: (i) Thermal fluctuations present in every physical and chemical system, (ii) anomalous fluctuations caused by random variations near chemical instabilities, (iii) stochastic delay and (iv) random drift in mutation space. Anomalous fluctuations and stochastic delay are consequences of autocatalytic processes at low particle numbers and disappear when the numbers of initially present particles are increased but are less sensitive to total population sizes. Initial conditions in epidemiology may determine the outcome of an epidemic. Stochasticity undermines "selection of the fittest" and we are left with probability distributions of being selected. Random drift, in principle, is also a finite size effect but unrealistically large populations would be required for coming close to the deterministic limit. Nature circumvents very low probabilities of transition by preparation of specific initial states from which transitions are less improbable. Representative examples of the four sources of randomness will be discussed.

Beyond the second law: Probability in stochastic thermodynamics

Udo Seifert
University Stuttgart

In a classical formulation, the second law of thermodynamics stipulates that in a spontaneous process the total entropy cannot decrease. According to a more refined understanding taking into account fluctuations, the entropy can indeed decrease, but it does so with only a small probability in repeated realizations of the process.

I will describe the comprehensive, quantitative theory, often called stochastic thermodynamics, that has been developed over the last 20 years to describe such spontaneous, and also driven, processes for systems on the micro- and nano-scale. In this framework, probability distributions, both for initial conditions and for trajectories evolving from them, play a central role. The general results, like the Jarzynski relation (1997) and the fluctuation theorem for entropy production (1993-2005), will be illustrated with experimental data from colloidal particles and molecular motors.

Where do all these distribution functions come from?

Stefan Thurner
Medical University of Vienna

We present a simple theory of driven out-of-equilibrium systems which are often at the core of complex adaptive systems. We show that driven systems that are composed of a driving process and a relaxation process, generically produce power law distributions for low driving rates. From the interplay of the driving rate with the relaxation processes we are able to understand the dynamical origin of a variety of distribution functions, including the power law, the Gamma, the Weibull, the Tsallis, the stretched exponential, the log-normal and many more distribution functions. We show simple examples where these insights are practically applicable, such as in understanding statistics of search processes, sentence formation, fragmentation phenomena, and the energy distribution of cosmic rays.

The interpretation of probability

Jos Uffink
University of Minnesota

This talk aims to introduce, in a historical context, the four main current views on the meaning of probability, as well as the problems that plague each of those views. I will argue that while all these views could in principle coexist peacefully, it is in the realm of statistics that they tend to clash.

P(paradox) = 100%

Sylvia Wenmackers
KU Leuven

In this talk, I revisit some well-known puzzles of probability, including: Bertrand-style paradoxes (based on the principle of indifference), Borel-Kolmogorov-style paradoxes (which involve conditioning on null events), and puzzles involving observer selection effects. My aim is to point out hidden connections between different corners of the probabilistic puzzle space.

Calibration and Confirmation in Climate Science

Charlotte Werndl
University of Salzburg

We argue that concerns about double-counting—using the same evidence both to calibrate or tune climate models and also to confirm or verify that the models are adequate—deserve more careful scrutiny in climate modelling circles. It is widely held that double-counting is bad and that separate data must be used for calibration and confirmation. We show that this is far from obviously true, and that climate scientists may be confusing their targets. Our analysis turns on a Bayesian/relative-likelihood approach and model selection theory. According to this approach, double-counting is entirely proper. We go on to discuss plausible difficulties with calibrating climate models, and we distinguish more and less ambitious notions of confirmation. Strong claims of confirmation may not, in many cases, be warranted, but it would be a mistake to regard double-counting as the culprit.

The Tension between the Subjective and Objective Views of Chance

Sandy Zabell
Northwestern University

The great Pierre Simon Marquis de Laplace (1749-1827) advanced a subjective view of the nature of probability:

"The word 'chance' then expresses only our ignorance of
the causes of the phenomena that we observe to occur and

to succeed one another in no apparent order. Probability
is relative in part to this ignorance, and in part to our knowledge."

But after Laplace's death questions about this position began to be raised: if probability is subjective,

1. How do we account for the existence of apparently objective chances (such as those associated with dice or roulette)?

2. What accounts for the success of statistical mechanics?

3. How do we measure subjective belief and why should we expect agreement among different people to ever occur?

In this talk I discuss how some of these problems were addressed in the century after Laplace's death: the introduction of the method of arbitrary functions by von Kries and Poincaré (to address the first); the use of the Ehrenfest urn model by Paul Ehrenfest to explain the reversibility and recurrence paradoxes of Loschmidt and Zermelo (to address the second); and the contributions of Ramsey and de Finetti to put our knowledge of subjective probability on a firm foundation (to address the last).