In Defense of Uncertainty:

Cosmic Structures, Information Geometry and the Possibility of Science

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> What I do not know I do not think I know either
>
> - Plato's account of Socrates,
> *Apology 29c-d* (Henry Caral's literal translation of 1897)

> Even when the dice are cast in circumstances of eternity, as when we contemplate the constellations of the cosmos, or cast in circumstances of complete and personal particularity, as when we seal our own fate, chance pours in at every avenue of sense.
>
> - Ian Hacking
> *The Taming of Chance*

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1 À Propos Probabilities

There is a tweet (Fig. 1) by Nicholas Nassim Taleb - a mathematician and risk analyst - that gestures at something provocative. When shown a figure mapping cross citations between disciplines [1, 2] and being asked what is the science that connects them all, Taleb responded: *Probability Theory.* There is something compelling about this reply, but it falls short of the complete picture. Probability theory does not possess the same epistemic warrants [3, 4] as many empirical sciences — but then again, neither do all sciences share a common epistemic virtue among themselves. Still, probability theory and statistical formalisms undergird our knowledge-making endeavors in one essential respect: they remain *the* mathematical engines for reasoning under uncertainty.

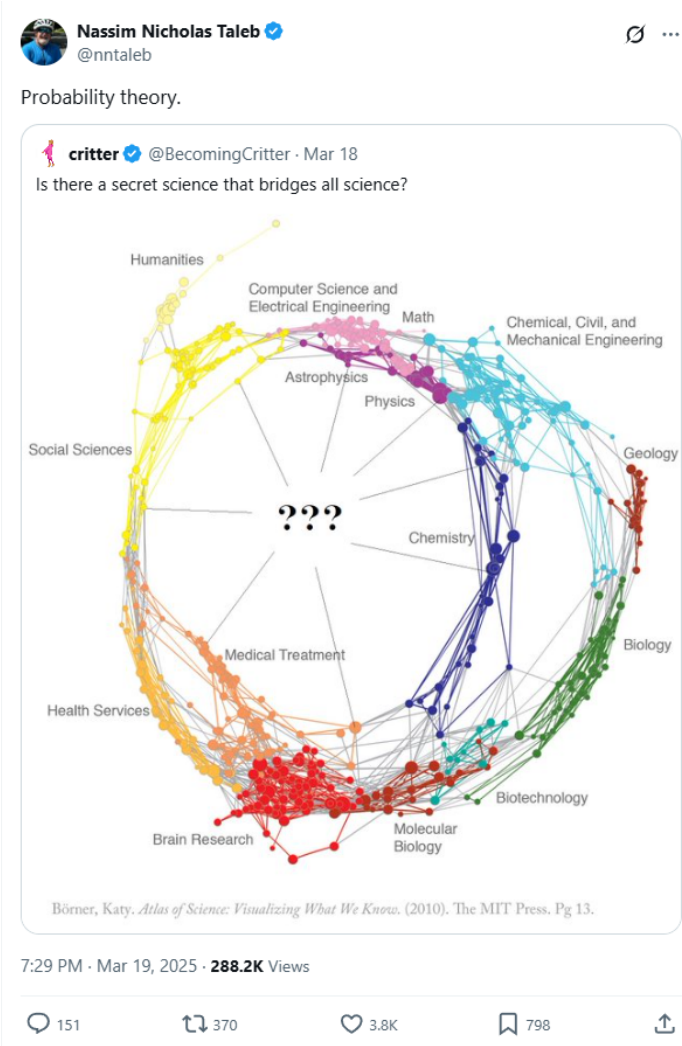

Figure 1: Taleb's response to a cartography of scientific disciplines [1]

The scientific enterprise is founded on and is propelled by uncertainty - that which we *take* to be certain rarely requires further investigation. Equally importantly, every pursuit of knowledge - from metaphysics to logic, quantum field theory, cosmology, psychology or career counseling - is inescapably entangled with uncertainty. The largest structures in the universe - galactic super-clusters and cosmic filaments - are probed using statistical tools (like correlation functions). At the other extreme of scales, the quantum laws governing electrons and quarks reveal themselves through probabilistic data. And outside physics altogether, the dynamics of stock markets and sports teams resist precise prediction, yielding only to statistical inference and aggregations. Across domains, uncertainty is not a mere limitation—but the very structure through which knowledge becomes accessible.

Unfortunately, precisely through this ubiquity and subtlety, uncertainty can be - and often is - weaponized. It takes the form of manufactured doubt to serve corporate interests, or of artificial certainty to manipulate public policy [5]. When decision-makers, tasked to navigate a random world, remain willfully ignorant of our best tools for understanding randomness, societies become fragile, exposed and easily misled. As Samuel S. Wilks presciently noted in his 1951 address to the American Statistical Association—paraphrasing H. G. Wells' *Mankind in Making*—'*Statistical thinking will one day be as necessary for efficient citizenship as the ability to read and write.*'

I hope to have persuaded the reader that all science is, at its core, statistical—the all-important error bars attached to our most precise measurements serve as reminders that we are still dealing with distributions, albeit tightly constrained ones. A serious engagement with probability and statistics is therefore essential to any holistic understanding of the world. Yet, in my own education at least, the aesthetics of statistics suffered from poor publicity. The standard introductions are technically correct, easy to follow but stylistically uninspiring. What captivated me in physics education were the questions probing the structure of bare reality: the texture of space and time, the origins of our universe. Statistics, by contrast, were the perfunctory obligations appended to my lab reports. It took me many years to recognize that the mathematical tools of uncertainty could be just as elegant, just as profound, as other exotic scientific objects like black holes or quantum entanglement.

There are, of course, many compelling examples that showcase how modern science operationalizes uncertainty—Bayesian formalisms, quantum computing, and more. The selection that follows is a deliberate curation, guided by a sense of which questions a curious undergraduate is least likely to encounter on their own. I offer two brief illustrations of the kind of statistical reasoning that I now regard every bit as beautiful as the more traditionally glamorous aspects of physics research.

2 Statistical Architecture of the Universe

Anyone with an undergraduate background in physics has likely already been exposed to the reverence accorded to the noble aspirations of statistical mechanics. Though its technical machinery may initially appear dizzying, its implausible success borders on the miraculous. From the unthinkable chaos of countless particles, in ceaseless motion and collisions, emerges an order that can be cast into a wholly intelligible handful of macroscopic parameters.

Most of our understanding of fluids arises from the formalisms of statistical mechanics. And, from a physicist's perspective, the concept of a fluid applies far beyond the everyday cases of liquids and gases. Protoplanetary disks and stellar nebulae—structures that eventually coalesce into planets and stars—also exhibit fluid-like behavior when viewed over long enough timescales. Even galaxies, as seen in simulations of events like the Andromeda–Milky Way collision, display a kind of slow, fluid-like evolution on cosmic timescales.

In fact, if one writes down the Boltzmann equation—a cornerstone of statistical physics—on a spacetime background modeled by the perturbed FLRW metric (which approximates the large-scale structure of our universe), the result is the Einstein–Boltzmann equations[6]. These are the governing laws of structure formation in cosmology. It is remarkable that a conceptual lineage beginning with gases and heat engines now yields the assembly history of the largest pieces in the web-like architecture of our cosmos.

Beyond the fact that the foundational principles of cosmology are inherited from statistical physics, there is yet another sense in which cosmology—even in its era of high-precision observations—remains a fundamentally statistical science. Consider one of its central observables: the *matter power spectrum*[7]. In general terms, the power spectrum measures the relative abundance of large (slowly varying) structures compared to smaller (rapidly varying) ones. Formally, it is the Fourier transform of the two-point correlation function, mapping the distribution of particles in real space to their spatial frequencies in k-space. A more intuitive picture would be the following: imagine a galaxy somewhere in the universe. Now extend a stick from that galaxy. What is the probability of finding another galaxy at the other end? How does that probability change as we vary the length of the stick? This is the kind of question the power spectrum answers—it tells us how many such 'sticks' of various lengths are statistically admitted by the matter distribution of our universe.

We can predict the shape of the power spectrum using the laws of statistical physics, and we can construct unbiased estimators to extract it from cosmological data. By comparing theoretical models of its evolution with observations of progressively distant galaxies, we refine our understanding of large-scale structure formation. A similar statistical machinery is applied not only to matter distribution but also to temperature fluctuations in the cosmic microwave background—opening an unprecedented window into the structure and history of the universe we inhabit.

One of my master's theses focuses on refining a technique to detect subtle distortions in the power spectrum caused by general relativistic effects. These distortions, small as they are, carry information about how the motion of our local cosmic neighborhood deviates from the idealized Hubble flow. This unlocks a novel independent measurement of our peculiar velocity i.e. our own motion through the 'grand scheme of things' [8].

Many layers of technical machinery are required to extract such a delicate signal.

Yet, in the spirit of Taleb's remark from the introduction, if I had to name one theme that unifies these different tools and insights, it would be the statistical science of the uncertain—and the careful, principled handling of our ignorance.

3 Geometry of Information and Sloppy Models

Information geometry offers another elegant illustration of how expansive a serious operationalization of uncertainty can be. Though relatively young as a discipline, its roots can be traced back in several different directions. It draws on Claude Shannon's formalization of information, while employing the mathematical language of differential geometry developed by Gauss and Riemann.

Information theory [9] was originally developed by Claude Shannon to analyze how transmission of data (i.e. information) is affected via noisy communication lines. However, because it formalizes ideas like predictability, redundancy, and order, it soon found applications well beyond telecommunication—refining our understanding of thermodynamic entropy, improving signal extraction in noisy experiments, and even informing the design of energy-based machine learning models.

Differential geometry [10], by contrast, provides a rigorous language for doing calculus on highly non-trivial spaces. It generalizes familiar notions—limits, derivatives, integrals, vectors—to settings where the underlying space might have holes, curvature, or more exotic features. One begins with a bare set of points—a manifold—and equips it with additional structure to make it suitable for their use. In general relativity, for instance, spacetime is modeled as a four-dimensional pseudo-Riemannian manifold endowed with a dynamical metric field and a Levi-Civita affine connection. These structures allow us to define rods and clocks at each point, compare the lengths of curves, and write down Einstein's field equations, which describe how matter bends spacetime and thus affects motion.

Now imagine replacing the familiar four-dimensional manifold of spacetime with a higher-dimensional abstract space, where each dimension corresponds to a parameter in a statistical model. This brings us closer to the domain of information geometry. The central idea is to take the likelihood functions associated with an experiment and endow the resulting parameter space with a geometric structure—a statistical manifold—from which non-trivial insights can be extracted, an example of which I will describe soon.

To study this manifold, we use the *Fisher information Matrix*: a tool developed to quantify how well observations can constrain the parameters of a model. If scientists are to justify billion-euro missions like Euclid or LISA, they must first demonstrate that the proposed surveys can, in principle, meaningfully measure the desired physical quantities. In certain regimes, the Fisher matrix satisfies all the desiderata of a metric (it is bilinear, symmetric, and non-degenerate). When we endow the statistical manifold with this Fisher metric, we are, in effect, defining the distance between two points (i.e. models) in the abstract space as a measure of how distinguishable their predictions are under observational data.

Once the fundamental machinery of information geometry is in place, its applications span a wide range of fields—machine learning, cosmology, biophysics, and beyond. One of my personal favorites is its role in analyzing so-called sloppy models—an approach that offers striking insights into the behavior of emergent systems.

Condensing this remarkable line of work into a few sentences feels almost sacrilegious. As a gesture of penance, I urge the reader to explore the short and wonderful paper by Transtrum et al.[11], and to browse James Sethna's group website[1] at Cornell, where much of this research has flourished. But here is the essential idea.

A wide class of multiparameter systems that exhibit emergent behavior—including biological networks, neural architectures, and even Ising models—show a characteristic spectrum of Fisher information eigenvalues. These eigenvalues span many orders of magnitude, and they naturally divide into stiff and sloppy directions. The stiff directions correspond to parameter combinations that are tightly constrained by data; the sloppy ones, to directions where large parameter changes leave predictions mostly

[1]https://sethna.lassp.cornell.edu/research

unchanged.

Consider how, in fluid dynamics, the overwhelming complexity of microscopic interactions becomes irrelevant at macroscopic scales. A handful of stiff parameter combinations—such as number density, mean velocity, and diffusion constant—are sufficient to describe experimental results with remarkable accuracy. These are the variables of the continuum theory, and their success stems precisely from the irrelevance of the underlying microscopic chaos.Such effective field theories—constructed through continuum limits or renormalization group procedures—are so ubiquitous in physics that one might reasonably claim all successful theories above the Planck scale are merely effective descriptions.

What information geometry offers—especially through the lens of sloppy models—is a framework for generalizing this insight. It helps us identify which emergent structures in complex domains like ecology, macroeconomics, and neuroscience are amenable to similar forms of compression. In doing so, it provides a principled account of emergence as parameter space compression [12]: the idea that only a few stiff directions govern the behavior of a system, while the vast majority can be ignored without sacrificing predictive power. This perspective enables the construction of simple, effective theories that coarse-grain overwhelming complexity into tractable models—without forfeiting explanatory depth. As James Sethna compellingly argues [13], it is this sloppiness that makes science possible in the first place: it affords us a meaningful notion of *useful but incomplete* understanding, where models can be predictive even when they are not complete or completely precise.

4 Speculative Metaphysics of Uncertainty

Having taken a brief tour through our attempts to understand both the largest structures of the universe and the molecular intricacies of life—along with much in between—I hope to have conveyed how statistical formalisms for taming uncertainty have become indispensable across science. Having discussed two technical tools at the frontier of this enterprise, I now wish to conclude with a more speculative reflection on the metaphysics of uncertainty itself.

A caveat is in order: there exists a vast philosophical literature on the nature of probability and the broader field of epistemology. What follows is written in full awareness of my ignorance of that scholarship—due less to conceptual oversight than to the temporal constraints of drafting these early thoughts. Still, for whatever it may be worth, and irrespective of whether the ideas here have been dismantled or independently rediscovered countless times, I find the following perspective both appealing and worth sharing.

Our relationship with uncertainty is deeply tied to the mind's peculiar ability to generate modal realities—possible worlds that go beyond immediate experience. The pervasiveness of uncertainty in epistemic pursuits is not solely a consequence of reality's inherent complexity; it also arises from our capacity to imagine alternative, equally intricate variations of any given account. This generative imagination is precisely why those operating at the frontiers of knowledge often experience the most profound uncertainty. It is often the novice who clings most tightly to certainty. One finds far more unwavering atheists among high school science students than among emeritus academics—many of whom, over time, develop subtle, and sometimes strange, ontological commitments to the transcendent[2].

Socrates famously declared, "I know that I know nothing." Almost twenty-five centuries later, we still do not know whether probabilities are real—nor do we even fully know how to pose that question rigorously [14]. Yet we go on generating answers, only to find that each one opens onto further questions. And so it goes.

Perhaps, then, it is not too far-fetched to suggest that what makes life intellectually meaningful is not the impossible aspiration to conquer uncertainty, but our capacity to imagine alternatives—to instantiate other possible ways things might have been, or still could be. It is not despite uncertainty, but precisely through it, that our

[2] I am not speaking only of philosophical figures like Spinoza, Jung, Lewis, or Kant, but also of scientists like Pauli, Bohr, Einstein, and Weyl.

understanding deepens and our lives become so rich with wonder.

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