Physics as Information Geometry on Causal Webs (Sketch of a Research Direction)

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Abstract

A high-level outline is given, suggesting a research direction aimed at unifying the Standard Model with general relativity within a common information-based framework. Spacetime is modeled spacetime using discrete "causal webs", defined as causal sets that have ternary rather than binary directed links, and a dynamic in which each ternary link propagates local values from its sources to its target using multiplication in an appropriate algebra. One then looks at spaces of (real and complex) probability distributions over the space of "causal web histories." One can then model dynamics as movement along geodesics in this space of probability distributions (under the Fisher-Rao metric).

The emergence of gravitation in this framework (as a kind of "entropic force") is derived from Matsuoka's work founding General Relativity in information geometry; the emergence of quantum theory is largely implicit in work by Goyal and others founding the basic formalism of quantum states, measurements and observables in information geometry. It is suggested that these various prior works can be unified by viewing quantum theory as consequent from information geometry on complex-valued probability distributions; and general relativity as consequent from the geometry of associated real probability distributions. Further, quantum dynamics is known to be derivable from the correspondence principle and basic properties of classical mechanics; but the latter is an approximation to general relativity – which as Matsuoka has shown is information-geometric, thus strongly suggesting that quantum dynamics also can be seen as emergent from information geometry. It is hypothesized that the Standard Model, beyond basic quantum mechanics, could potentially be obtained from this approach via appropriate choice of the "local field" algebra propagated within the underlying causal webs.

In addition to mathematical elegance, this approach to physics unification has the conceptual advantage of highlighting the parallels between physical dynamics and mental inference (given the close ties between Bayesian inference and information geometry).

Contents

1 Introduction

The idea of founding physics in the theory of information, in some sense or another, is no longer particularly radical [12] [24]. However, the prevailing paradigms of research on the "grand unification" of general relativistic gravitational theory with quantum theory and its extensions (quantum field theory and the Standard Model), string theory and loop quantum gravity, are not directly informational in nature. Here I argue for grand unification via founding the various physics theories involved directly in an information-theoretic framework.

I will draw together here two strains of recent physics thinking, both rich and diverse in themselves. One is information geometry; the other is causal set theory.

Regarding information geometry: Various prior authors have shown, separately, that both general relativity (GR) and quantum mechanics (QM) can be formulated formulated in terms of the Fisher-Rao metric (the natural metric on the space of probability distributions, which lies at the heart of information geometry theory [1]). There are significant differences in how GR and QM present themselves information-geometrically, e.g. regarding the role of complex-number amplitudes in quantum dynamics. However, it seems that

[1] I will make no effort to outline the basic ideas of information geometry here. The classic reference is Amari's book [1]. The Wikipedia pages on Information Geometry [2] and Fisher Information [3] are reasonably explanatory for the reader who has some familiar with statistics and differential geometry. John Baez has also presented an excellent online tutorial in a series of blog posts [3] [4].

these differences can be managed, enabling GR and QM to be viewed as different aspects of the same geometric dynamics on probability distribution spaces. Further, the Lorentzian structure of spacetime can be seen to emerge naturally from the nature of the Fisher-Rao metric as applied to the relevant types of probability distributions.

Causal sets, on the other hand, are a simple discrete model that appears a strong candidate as a discrete analogue of continuous spacetime [13]. The mathematics of causal sets and dynamics thereupon has been explored significantly in recent years [26]. However, by and large, it's fair to say that causal set theory mainly provides a structure and doesn't say much about dynamics. I suggest here an extension to causal sets called *causal webs*, that replaces the binary arrows in causal sets with ternary arrows, and models low-level dynamics in terms of abstract-algebraic operations on these arrows (i.e. the local-field values at the source of an arrow, multiply to yield the local-field value at the target of the arrow).

Putting these two strains together, one can look at **spaces of real and complex valued probability distributions over spaces of causal web histories**. I hypothesize that physics can be effectively modeled in terms of information geometry on such spaces.

This is blatantly a concept paper rather than a detailed treatment; the ideas given here are speculative with many gaps to be filled.

Speculating even further, I suggest these ideas might also have value as a means of exploring the relation between physics and intelligence, given the role of Bayesian inference and information geometry in models of cognition, and the generally vexatious nature of mind-world interactions in quantum measurement as modeled within current physics paradigms.

I will proceed here from the "top down" – beginning with ways of viewing gravitation and quantum theory in terms of information geometry; and then moving on to the question of what is the fundamental space over which one's probability distributions are defined (I suggest causal web histories).

2 General Relativity from Information Geometry

The most promising direction regarding grounding *gravitational* physics in informational concepts, appears to be recent work connecting general relativity with entropic and information-geometric mathematics.

In 2011, Verlinde published a paper on "gravitation as an entropic force" [25], which attracted considerable attention to a line of research that had been around for some time [11] [17]. Thanu Padmanabhan is perhaps the best known researcher in this area, and his recent paper "General Relativity from a Thermodynamic Perspective" contains an up-to-date and fairly thorough literature review [16] [5].

[5] http://arxiv.org/abs/1312.3253

However, the most explicit connection between gravitation and the Fisher-Rao metric has been drawn in a 2013 paper by Hiroaki Matsueda, titled "Emergent General Relativity from Fisher Information Metric" [15] [6]. In this work, Matsueda shows that the Fisher-Rao metric between two appropriately defined distributions from the exponential family (on 3D space) gives rise to the Einstein equations (the crux of General Relativity) on 3+1D spacetime. As he put it, he derives the Einstein equation directly as the equation of "coarse-grained quantum state."

In the discrete case, he considers a system with internal state depending on a parameter vector

$$\theta = (\theta_1, , \theta_n)$$

and n possible measurement outcomes with probabilities

$$p_i(x, \theta)$$

that sum to 1. He derives the Einstein equation from the Fisher-Rao metric of such distributions; and, looking at an exponential distribution

$$p(x, \theta) = e^{\left(\sum_\mu \theta_\mu F^\mu\right) - \phi(\theta)}$$

he does some nice analysis to conclude that ϕ behaves like a classical scalar field.

Matsueda's analysis is not without technical issues; for instance, his equation [80] appears to be a fairly crude approximation without a rigorously given justification. While it appears essentially correct, his derivation seems to require some tightening. But it represents a highly evocative direction of investigation.

3 Lorentzian Spacetime from Information Geometry

Closely related to Matsueda's calculations, in 1998 Carlos C. Rodriguez [21] [7] provided an elegant mathematical demonstration that the 3+1 dimensional structure of spacetime emerges naturally from the mathematics of the Fisher-Rao metric on spaces of radially symmetric probability distributions. He looks at Gaussian (or other radially symmetric) distributions on 3D space, and considers them as a space under the Fisher-Rao metric; and then shows that this leads to matrices looking suspiciously like familiar 3 space dimensions, 1 time dimension matrices from physics. This leads him to the tantalizing aphorism "There is no time, only uncertainty."

In essence, Rodriguez's probability distributions are characterized by a single radial dimension, and then the three-dimensional location of the distribution's

[6] http://arxiv.org/pdf/1310.1831v2.pdf
[7] http://arxiv.org/abs/physics/9808009

mean. When the Fisher-Rao metric is calculated, the algebra comes out equivalent to the consideration of the radial dimension as imaginary, compared to the other three dimensions being real. So one recovers the structure of Minkowski space, without really trying.

While Rodriguez's calculations pertain to strictly radially symmetric distributions, it seems likely that the same results will hold for other distributions that are characterized via a 3D mean, and then a single real parameter governing deviation from the mean, whether or not strict symmetry holds. For instance, one suspects that a similar Minkowski-like property would emerge from the exponential distributions that Matsueda studies, mentioned above.

4 The Mysterious Complex-ity of Quantum Mechanics

Excitingly, as I will review in Section 5 below, it also seems feasible to derive many of the key aspects of quantum mechanics from information-geometric mathematics. However, significant and intriguing subtleties emerge here due to the role of complex numbers in quantum mechanics. This should not be surprising since, generally speaking, most of the perplexing "mystery" of quantum mechanics can be boiled down to QM's use of complex numbers where one would intuitively expect to see real numbers, in the connection of quantifying degrees of uncertainty.

The usage of complex numbers to quantify uncertainty can be justified or formalized in various ways. For example, Lucien Hardy [10] [8] derives quantum theory from a small set of commonsensical axioms, plus the idea that time is infinitely divisible, in the sense that there should exist continuous transformations between (pure) states. The core idea here has been summarized by Scott Aaronson on his blog [9] , in the context of presenting a number of reasons why Nature uses complex instead of real numbers to measure uncertainty, including the assumption that

"for every linear transformation U that we can apply to a state, there must be another transformation V such that $V^2 = U$. This is basically a continuity assumption: we're saying that, if it makes sense to apply an operation for one second, then it ought to make sense to apply that same operation for only half a second"

This continuity assumption, it turns out, yields pretty simply the conclusion that one needs to work with complex rather than real numbers.

Saul Youssef [28] [29] [10] has shown that, if one takes all the standard axioms of probability theory except the one saying a probability has to be a real number, one can also get three exotic probability theories with complex, quaternionic and octonionic probabilities respectively. Furthermore, he has shown that, if

[8] http://arxiv.org/abs/quant-ph/01010

[9] http://www.scottaaronson.com/democritus/lec9.html

[10] see a list of Youssef's relevant papers at the end of the directory page http://physics.bu.edu/~youssef/quantum/quantum_refs.html

one assumes probabilities are measured via complex numbers, then in essence quantum theory (the Schroedinger equation) basically falls right out.

John Baez has demonstrated that Feynman's formula for the amplitude of a path being followed by a quantum system, is equivalent to the principle of stationary "quantropy" [4] [11] – where what he means by "quantropy" is complex valued entropy, i.e. entropy on complex numbers. This is basically entropy on complex-valued "exotic" probabilities, although Baez doesn't call it that. To find the distribution of amplitudes across the various paths a quantum system might take, look for the distribution that has stationary quantropy – subject to the constraints that the sum of the amplitudes of the various possible outcomes is 1; and that some weighted sum of the amplitudes has a fixed value (note that he calls the weights the actions of the outcomes; and calls the outcomes histories).

Note that Baez doesn't show that a quantum system follows a path that makes quantropy stationary. What he shows is that the (complex) probability distribution over possible paths (or "histories", which is a clearer term than "paths" in quantum ontology) x is a stationary-quantropy distribution, which looks like

$$a(x) = e^{-\lambda A(x)/Z}$$

where Z is a partition function and λ is a (real) parameter called the "classicality."

Unsurprisingly, the exponential distribution Baez derives from his stationary-quantropy formalism, has the same basic form as the distribution Matsueda assumes for his probability distributions, from which he derives GR (this is unsurprising because they're both taking their cue from the Boltzmann equation). The only big difference is that Baez's distribution is complex-valued, whereas the distribution Matsueda looks at is real-valued. Also, Matsueda looks at a more general distributional form, leaving room for more parameters, which is useful if one wants to take into account a fuller spectrum of microphysical phenomena.

It would appear, however, that Matsueda's math would work perfectly well if one began with a probability distribution outputting exotic, complex-valued probabilities instead. So if one wished, one could likely take Baez's exotic quantum distributions and use them as the basis for a Matsueda-style analysis.

5 Quantum Theoretic Apparatus from Information Geometry

In his paper "From information geometry to quantum theory. Philip Goyal [9] [12] has shown that one can derive the basic mathematics of quantum states, observables and measurements from a series of assumptions, one of which is

[11] `http://arxiv.org/pdf/1311.0813v2.pdf`

[12] `http://iopscience.iop.org/1367-2630/12/2/023012/fulltext/`

that changes of state should preserve distances in the Fisher-Rao metric, on the space of probability distributions corresponding to the probabilities of possible outcomes of measuring a system. This shows that much of the apparatus of quantum mechanics can be derived from information geometry, in a simpler and more direct way than Matsueda's derivation of the Einstein equation from information geometry.

Goyal's use of information geometry relies directly and essentially on the well-known fact that the Fisher-Rao metric is equivalent to the Euclidean metric, after an appropriate change of variable.. The Euclidean metric on square roots of probabilities, essentially gives you the Fisher-Rao metric on probabilities (a fact that is often obscured due to the Fisher-Rao metric generally being given in parametric form). Quantum-mechanical amplitudes are related to square roots of probabilities. Quantum observation is based on multiplication by unitary matrices on complex vectors, which need to preserve Euclidean distances in complex vector space; but this corresponds precisely to preservation of the Fisher-Rao metric in the space of squares of the complex vector entries. So, the quantum theory axiomatics aside, the appearance of information geometry in Goyal's paper emerge elegantly and fairly straightforwardly from the mathematical correspondence of the Fisher and Euclidean metrics.

The relation between Goyal's treatment and Baez's, mentioned above, is interesting and slightly subtle. Goyal uses the fact that QM's orthogonal observation transformations on complex amplitude space are, in essence, equivalent to Fisher-Rao-metric-preserving transformations on real probability space. Baez looks at complex-valued entropy and shows that QM's distribution of amplitudes to possible paths is a stationary-complex-entropy distribution. What Goyal shows is that the amplitudes assigned by Baez's distribution are transformed under observation via orthogonal transformations, which correspond to Fisher-Rao-metric preserving distributions on real numbers corresponding to these amplitudes.

There does not seem to be a fleshed-out formal theory of information geometry on complex probability distributions, such as the ones Baez looks at. However, it seems very likely that the key results of information geometry will continue to hold if the real probabilities are replaced with complex ones [13]

6 Quantum Dynamics via a Correspondence Principle

Goyal [9], discussed above, derives the apparatus of quantum states, observations and measurements from information-geometric assumptions, but doesn't derive the Schroedinger equation or any other formulation of quantum *dynamics*. However, in a follow-up paper [8] [14], Goyal does derive the Schroedinger equation in a related way, via connecting his information-geometric analyses

[13] Replacing them with quaternionic or octonionic probabilities might lead to subtler issues.
[14] `http://arxiv.org/abs/0805.2765`

with a version of the Correspondence Principle – in essence, deriving quantum dynamics from the combination of information-geometric assumptions, and the assumption of agreement with classical mechanics in the statistical limit.

In their paper "Information geometry, dynamics and discrete quantum mechanics, Reginatto and Hall present a similar derivation of quantum theory from information geometry, using different axioms [20] [15]. Like Goyal, they simplify things by looking at the discrete case, which is however sufficient for explaining all experiments. And also similar to Goyal, but in this respect more elegantly, they derive quantum dynamics via the requirement to generate the symplectic structure of Hamiltonian dynamics in the statistical limit.

6.1 General Relativity and the Correspondence Principle

While the correspondence principle is normally formulated using classical mechanics, it has also been articulated using general relativity as the "classical" limit of quantum theory [7]. Furthermore, it is known that GR has symplectic structure [2] [16], similar to that of classical, Hamiltonian dynamics, though more complex to unravel. This suggests (but doesn't quite prove) that the use of "agreement with classical physics in the limit" as a method of deriving the Schroedinger equation from the basic apparatus of quantum states and observables, a la Goyal, could be done equally well using "agreement with GR in the limit, under appropriate conditions" instead. This is interesting in the present context, because if Matsueda is correct then GR can be derived from information geometry. So, if

- information geometry gives us both GR, and the basic states/observables machinery of QM
- putting GR and basic QM states/observables machinery together yields the equation of quantum dynamics

then, putting the pieces together (and sweeping just a few "details" under the rug!), one has a derivation of GR and QM both from underlying information-geometric assumptions.

7 Putting Together the Information-Geometric Pieces

What happens when we put these various information-geometric pieces together?

Adjusting Matsueda's formalism slightly, lets initially look at a discrete system, with internal state depending on a parameter vector

$$\theta = (\theta_1, , \theta_n)$$

[15] http://arxiv.org/abs/1207.6718
[16] http://arxiv.org/abs/gr-qc/0109014

and n possible measurement outcomes with complex-number *amplitudes*

$$a_i(x,\theta)$$

that sum to 1. If we assume that local complex-probability distributions are chosen to make complex-valued entropy stationary, then we arrive at a collection of complex exponential distributions, with different means, of the form

$$a(x,\theta) = e^{\left(\sum_\mu \theta_\mu A^\mu\right) - \phi(\theta)}$$

Performing a Matsueda-like derivation on such a complex-valued distribution, would yield a variant of the Einstein equation on complex vectors; standard GR would ensue from looking at the real parts.

If we have a parameter θ_i that behaves roughly like a radial variable (such as the classicality, which emerges naturally from stationary complex-entropy as Baez shows), then, following Rodriguez, the corresponding component in the matrix representing the Fisher-Rao metric will likely behave like a time coordinate in Minkowski space.

Quantum observation of a local system involves transformation that orthogonally transform the amplitude values, which, as Goyal notes, means they preserve the Fisher-Rao metric on the underlying real values. As Matsueda's model of gravitational dynamics involves gravitation pulling objects along shortest paths in Fisher-Rao metric space, this means that quantum observation leaves gravitational trajectories invariant (as it maps shortest paths into shortest paths).

The Schroedinger equation is a local approximation of classical dynamics in many circumstances; and one suspects, of GR in other circumstances. Classical fields emerge statistically via ϕ as Matsueda notes; and quantum dynamics emerges from looking at the complex amplitudes a_i on the smaller scale.

GR dynamics follows shortest paths in the Fisher-Rao metric emerging from the space of local distributions; complex QM dynamics follows paths within the local distributions that have emerged to maximize complex-entropy. Further, it is known that the shortest paths in the Fisher-Rao space are paths along which mutual information progressively increases [5].

The conventional objections to putting QM and GR together – that one regards linear transformations infinite-dimensional Hilbert space, whereas the other regards nonlinear dynamics on 4 dimensional spacetime – become wholly irrelevant in this framework. Both physical theories are viewed as having to do with dynamics on spaces of discrete probability distributions. This represents a more direct perspective, since experimentally, we don't have 4D continuous spacetime or infinite-dimensional Hilbert space, we just have discrete sets of measurements with various estimated probabilities.

7.1 Incorporating the Rest of the Standard Model

So far we have discussed basic quantum mechanics and general relativity. What about all the other aspects of the Standard Model, beyond ordinary QM? Very broadly speaking, many approaches would be possible here:

1. packing more complex structure into Matsueda's θ vector
2. moving to quaternionic or octonionic valued probability distributions, rather than the complex valued distributions used for quantum mechanics
3. move to a more fundamental framework, making different hypotheses regarding the space over which the probability distributions utilized extend

Regarding the quaternion/octonion possibility, it would be interesting to see if some analogue of Baez's quantropy-based analysis of QM, could be done using quaternionic or octonionic analogues of entropy, yielding e.g. chromodynamics as a result. Mathematical relationships between chromodynamics and these other division algebras hint at such a possibility [19] [17] [18] [18] but much remains unclear.

However, currently the direction that excites me most is the latter – moving beyond a continuous spacetime and continuous parameter vector model, and looking at how to formulate information-geometric physics over more fundamental discrete structures. This brings us on to the notion of causal webs.

8 Causal Webs

The above treatment has been fairly top-down and abstract, in the sense that it has described gravitation and quantum mechanics as potentially derivable from spaces of probability distributions – but hasn't gotten concrete about exactly what these probability distributions extend over. Further, while the treatment has been "informational" in the sense of relying on information geometry, it has also been somewhat traditional in its reliance on an underlying spacetime continuum, with respect to which the various probability distributions are implicitly defined.

Now I'm going to get more concrete, and also a bit more radical. I'm going to suggest a novel discrete model of the spacetime continuum and local fields defined thereon, and then propose that the information-geometric structures reviewed in previous sections can be made to play nicely on these novel discreta, which I call "causal webs."

The path to causal webs begins with causal sets, a well known approach to quantum gravity that is founded on a theorem by David Malament [14], stating that if there is a bijective map between two past and future distinguishing spacetimes that preserves their causal structure, this implies the map is a conformal isomorphism. Malament's theorem implies that the causal structure of a spacetime continuum, as used in relativity theory, can be captured a by discrete graph, in which two nodes are connected by an arrow if events at the source node can causally impact events at the target node.

[17] `http://arxiv.org/abs/1006.5552`

[18] `http://vixra.org/abs/1311.0101`

Sorkin [13] has been the primary driver behind the development of causal set theory, but the deepest and most rigorous treatment of the ideas has been given in a recent paper by Benjamin Dribus [6] [19]. As well as clarifying the formalism in a very elegant way, he defines a rather general propagator on causal sets, and formulates a causal-set analogue of the Schrodinger equation. Dribus's causal-set propagator deals with any map from chains (where a chain is a series of causal sets, each one extending its predecessor) into amplitudes. Roughly speaking, it has to do with the amplitude of one causal set C getting "grown" into another causal set C' via a sequential growth process (see [26] for an overview of sequential growth processes in causal set theory, and their use for formulating dynamics on causal sets). It allows background-independent Feynman sums to be made over spacetime discreta, via giving an amplitude distribution over causal sets representing such discreta.

Further, though Dribus does not explore the implications of this, his formalism also allows one to construct chains from elements that are tagged with particular structures – i.e. it covers the case where each node of the causal set is tagged with some sort of "local field value." This is potentially important, because one route to constructing a full theory of physics based on causal sets is to go beyond a causal set as *a bunch of nodes connected by arrows* and move to some sort of formalism involving *nodes, with multidimensional 'field' values attached to them, connected by arrows.* I.e. one might want to look at some sort of field defined over causal sets.

In fact my suggestion is to go one step further, and look at a "causal web" formulation wherein one has links like

$$\{A, B\} \to C$$

and the nodes A,B and C have structure S_A, S_B, S_C attached to it – representing the 'local field' information at the node A, B or C.

One may then posit a rule assigning an amplitude to each possible "transition"

$$\{S_A, S_B\} \to S_C$$

For instance, if one views the structures S_X as elements of an algebra with operator $*$, one can set

$$S_C(t+1) = S_A(t) * S_B(t)$$

where t represents a kind of "proto-time", distinct from (and underlying) the Lorentzian time of relativistic physics.

Then, given a causal web C' and a sub-web C of C', one could calculate the amplitude of C "growing" into C' – thus yielding an amplitude distribution over causal webs, similar to the amplitude distribution Dribus constructs over causal sets. It seems to me that Dribus's overall causal set formalism could be straightforwardly, if laboriously, extended to this sort of causal web...

[19] `http://arxiv-web3.library.cornell.edu/pdf/1311.2148v3.pdf`

I suspect one could show that continuous field theories, within fairly broad conditions, can be emulated by causal webs within arbitrarily small errors. Conceptually, causal webs are a bit like discrete reaction-diffusion equations; and it's known that discrete reaction-diffusion equations can be mapped into discrete quantum field theories. However, I'm not advocating this sort of approximation-theoretic analysis as the best route to develop causal web based physics.

Rather, I suspect that it may be possible to choose an appropriate abstract algebra, and make the S_X elements of this algebra. One promising option here is E8, which is know to contain the key algebras of the Standard Model within it in various ways [23] [20][18] [21]; but that is not the only option, and I haven't yet explored this carefully.

The proto-temporal dynamics of a causal web generates a *causal web history.*

8.1 Information Geometry on the Space of Causal Web Histories

Getting back to the information-geometric considerations discussed above – I suggest that causal web histories comprise a very interesting candidate for the role of the underlying space on which to construct the probability distributions information geometry requires. I suggest that it may be very interesting to look at (real and complex valued) probability distributions over causal web histories.

The distribution centered at a history C would assign an amplitude to C' based on the probability of growing C into C'.

Potentially, one could show that the maximum-quantropy distribution of this sort, has a Boltzmann-distribution-like form, where the "energy function" in the exponent of the distribution is derived from the underlying rules assigning amplitudes to the transitions $\rightarrow$ described above in terms of the algebraic operator $*$.

General relativity could then, perhaps, be seen to emerge Matsueda-like from the Fisher metric among these local distributions.

Putting all these pieces together, one would have a complete picture, comprising

- causal webs as underlying pregeometry, endowed with algebraic causal-web dynamics as proto-temporal pre-dynamics
- local spacetime as a stationary-quantropy amplitude distribution over causal web histories (where the causal webs are endowed with algebraic structures serving as discrete equivalents to fields)
- global spacetime as Fisher-metric space over these distributions
- quantum mechanics as linear dynamics on local spacetime
- gravitation as global, entropic (nonlinear) dynamics on this global spacetime

[20]ttp://vixra.org/pdf/1405.0030vD.pdf
[21]http://vixra.org/abs/1311.0101

9 Conclusion

I have presented here a complex train of thought connecting a number of existing research results, which themselves possess varying degrees of solidity. There are some substantial gaps in this train of thought, that are in need of filling-in via the performance of non-trivial mathematical derivations. In short, what is outlined here is more a direction for research than a completed theoretical development.

However, it should be noted that the most popular approaches to grand unification are also, at this point, highly speculative as well – and furthermore are significantly more complicated than the approach presented here. The information-geometric approach to grand unification proceeds relatively directly from the conceptual, philosophical idea of grounding physics in the geometry of the space of probability distributions. Physical laws are then seen to emerge from simple information-theoretic principles such as:

- preservation of the information metric
- choice of probability distributions that minimize (real or complex) entropy
- following geodesics in information-metric space

Implementing this in the context of causal webs enables a fully discrete, information-theoretic framework for modeling spacetime and the full gamut of physical dynamics occurring therein.

While plenty of work remains to be done to make the different pieces of this vision fit together, the simplicity and solidity of the information-geometric and causal-set-theoretic foundations outlined makes me optimistic that the research program outlined maybe possible to complete.

Furthermore, digressing a bit toward conceptual and interpretational issues, the parallels between inference (cognitive activity) and physical dynamics that the information-geometric approach reveals, are striking to say the least. Part of Wheeler's original motivation for proposing "it from bit" [27] was to help close the mind-world gap in physics theory. My strong suspicion is that a mature unified physics developed along the lines suggested here, would not only provide a unified basis for handling all the known forces, but would also provide a physical foundation for exploring the mind-body relationship in a deeper way that current physics theories allow.

Along these lines, one of the biggest mind/matter worries in modern science is quantum measurement. I tend to favor the relational interpretation of quantum mechanics [22], in which there is no wave function collapse, but the state of a quantum system is understood to be observer-dependent. In the proposed approach, both the system and the observer would be represented as probability distributions over causal web histories. Interaction would be reflected by probabilistic dependency between the distributions, and would be mediated by light cone considerations as embedded in the underlying causal webs. In this way, the decoherence-inducing interaction that characterizes quantum measurement, would represented in terms of a key aspect of probabilistic inference.

Lots of interesting possibilities and concepts! But at the present time, this is all just tantalizing conjecture. I have elaborated these ideas here in hope of inspiring others to join me in working out the details, a journey that no doubt will lead to many fascinating surprises.

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