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PBR, EPR, and all that jazz

Matt Leifer

In the past couple of months, the quantum foundations world has been abuzz about a new preprint entitled "The Quantum State Cannot be Interpreted Statistically" by Matt Pusey, Jon Barrett and Terry Rudolph (henceforth known as PBR). Since I wrote a blog post explaining the result, I have been inundated with more correspondence from scientists and more requests for comment from science journalists than at any other point in my career. Reaction to the result amongst quantum researchers has been mixed, with many people reacting negatively to the title, which can be misinterpreted as an attack on the Born rule. Others have managed to read past the title, but are still unsure whether to credit the result with any fundamental significance. In this article, I would like to explain why I think that the PBR result is the most significant constraint on hidden variable theories that has been proved to date. It provides a simple proof of many other known theorems, and it supercharges the EPR argument, converting it into a rigorous proof of nonlocality that has the same status as Bell's theorem. Before getting to this though, we need to understand the PBR result itself.

What are Quantum States?

One of the most debated issues in the foundations of quantum theory is the status of the quantum state. On the ontic view, quantum states represent a real property of quantum systems, somewhat akin to a physical field, albeit one with extremely bizarre properties like entanglement. The alternative to this is the epistemic view, which sees quantum states as states of knowledge, more akin to the probability distributions of statistical mechanics. A psi-ontologist (as supporters of the ontic view have been dubbed by Chris Granade) might point to the phenomenon of interference in support of their view, and also to the fact that pretty much all viable realist interpretations of quantum theory, such as many-worlds or Bohmian mechanics, include an ontic state. The key argument in favor of the epistemic view is that it dissolves the measurement problem, since the fact that states undergo a discontinuous change in the light of measurement results does not then imply the existence of any real physical process. Instead, the collapse of the wavefunction is more akin to the way that classical probability distributions get updated by Bayesian conditioning in the light of new data.

Many people who advocate a psi-epistemic view also adopt an anti-realist or neo-Copenhagen point of view on quantum theory in which the quantum state does not represent knowledge about some underlying reality, but rather it only represents knowledge about the consequences of measurements that we might make on the system. However, there remained the nagging question of whether it is possible in principle to construct a realist interpretation of quantum theory that is also psi-epistemic, or whether the realist is compelled to think that quantum states are real.

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PBR have answered this question in the negative, at least within the standard framework for hidden variable theories that we use for other no go results such as Bell's theorem. As with Bell's theorem, there are loopholes, so it is better to say that PBR have placed a strong constraint on realist psi-epistemic interpretations, rather than ruling them out entirely.

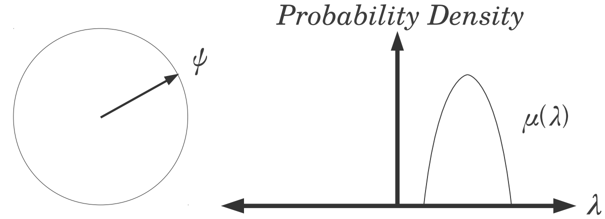

Figure 1. In a hidden variable theory, a quantum state (indicated heuristically on the left as a vector in the Bloch sphere) is represented by a probability distribution over ontic states, as indicated on the right.

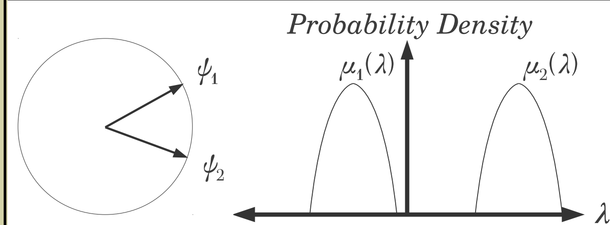

Figure 2. Representation of a pair of quantum states in a psi-ontic model.

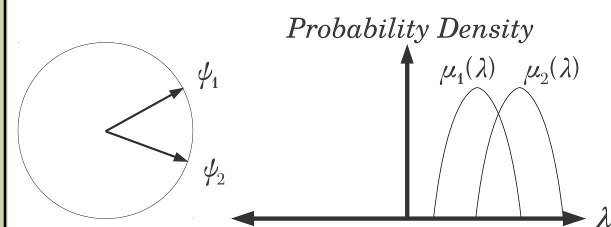

Figure 3. Representation of nonorthogonal states in a psi-epistemic model.

The PBR Result and its implications

To properly formulate the result, we need to know a bit about how quantum states are represented in a hidden variable theory. In such a theory, quantum systems are assumed to have real pre-existing properties that are responsible for determining what happens when we make a measurement. A full specification of these properties is what we mean by an ontic state of the system. In general, we don't have precise control over the ontic state so a quantum state corresponds to a probability distribution over the ontic states. This framework is illustrated in Figure 1.

A hidden variable theory is psi-ontic if knowing the ontic state of the system allows you to determine the (pure) quantum state that was prepared uniquely. Equivalently, the probability distributions corresponding to two distinct pure states do not overlap. This is illustrated in Figure 2. A hidden variable theory is psi-epistemic if it is not psi-ontic, i.e. there must exist an ontic state that is possible for more than one pure state, or, in other words, there must exist two nonorthogonal pure states with corresponding distributions that overlap. This is illustrated in Figure 3.

These definitions of psi-ontology and psi-epistemicism may seem a little abstract, so a classical analogy may be helpful. In Newtonian mechanics the ontic state of a particle is a point in phase space, i.e. a specification of its position and momentum. Other ontic properties of the particle, such as its energy, are given by functions of the phase space point, i.e. they are uniquely determined by the ontic state. Likewise, in a hidden variable theory, anything that is a unique function of the ontic state should be regarded as an ontic property of the system, and this applies to the quantum state in a psi-ontic model. The definition of a psi-epistemic model as the negation of this is very weak, e.g. it could still be the case that most ontic states are only possible in one quantum state and just a few are compatible with more than one. Nonetheless, even this very weak notion is ruled out by PBR. The proof of the PBR result is quite simple, but I will not review it here. Rather, I refer the interested reader to the references below and, instead, focus on its implications.

A trivial consequence of the PBR result is that the cardinality of the ontic state space of any hidden variable theory, even for just a qubit, must be infinite, in fact continuously so. This is because there must be at least one ontic state for each quantum state, and there are a continuous infinity of the latter. The fact that there must be infinite ontic states was previously proved by Lucien Hardy under the name "Ontological Excess Baggage theorem", but we can now view it as a corollary of PBR. If you think about it, this property is quite surprising because we can only extract one or two bits from a qubit (depending on whether we count superdense coding) so it would be natural to assume that a hidden variable state could be specified by a finite amount of information.

Hidden variable theories provide one possible method of simulating a quantum computer on a classical computer by simply tracking the value of the ontic state at each stage in the computation. This enables us to sample from the probability distribution of any quantum measurement at any point during the computation. Another method is to simply store a representation of the quantum state at each point in time. This second method is clearly

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inefficient, as the number of parameters required to specify a quantum state grows exponentially with the number of qubits. The PBR theorem tells us that the hidden variable method cannot be any better, as it requires an ontic state space that is at least as big as the set of quantum states. This conclusion was previously drawn by Alberto Montina using different methods, but again it now becomes a corollary of PBR. This result falls short of saying that any classical simulation of a quantum computer must have exponential space complexity, since we usually only have to simulate the outcome of one fixed measurement at the end of the computation and our simulation does not have to track the slice-by-slice causal evolution of the quantum circuit. Indeed, pretty much the first nontrivial result in quantum computational complexity theory, proved by Bernstein and Vazirani, showed that quantum circuits can be simulated with polynomial memory resources. Nevertheless, this result does reaffirm that we need to go beyond slice-by-slice simulations of quantum circuits in looking for efficient classical algorithms.

As emphasized by Harrigan and Spekkens, a variant of the EPR argument favoured by Einstein shows that any psi-ontic hidden variable theory must be nonlocal. Thus, prior to Bell's theorem, the only open possibility for a local hidden variable theory was a psi-epistemic theory. Of course, Bell's theorem rules out all local hidden variable theories, regardless of the status of the quantum state within them. Nevertheless, the PBR result now gives an arguably simpler route to the same conclusion by ruling out psi-epistemic theories, allowing us to infer nonlocality directly from EPR.

A sketch of the argument runs as follows. Consider a pair of qubits in the singlet state. When one of the qubits is measured in an orthonormal basis, the other qubit collapses to one of two orthogonal pure states. By varying the basis that the first qubit is measured in, the second qubit can be made to collapse in any basis we like (a phenomenon that Schroedinger called "steering"). If we restrict attention to two possible choices of measurement basis, then there are four possible pure states that the second qubit might end up in. The PBR result implies that the sets of possible ontic states for the second system for each of these pure states must be disjoint. Consequently, the sets of possible ontic states corresponding to the two distinct choices of basis are also disjoint. Thus, the ontic state of the second system must depend on the choice of measurement made on the first system and this implies nonlocality because I can decide which measurement to perform on the first system at spacelike separation from the second.

PBR as a proto-theorem

We have seen that the PBR result can be used to establish some known constraints on hidden variable theories in a very straightforward way. There is more to this story that I can possibly fit into this article, and I suspect that every major no-go result for hidden variable theories may fall under the rubric of PBR. Thus, even if you don't care a fig about fancy distinctions between ontic and epistemic states, it is still worth devoting a few brain cells to the PBR result. I predict that it will become viewed as the basic result about hidden variable theories, and that we will end up teaching it to our students even before such stalwarts as Bell's theorem and Kochen-Specker.

Matt Leifer *is a postdoc at University College London. He obtained his Ph.D. in quantum information from the University of Bristol in 2004, and has since worked at the Perimeter Institute, the University of Waterloo, and the University of Cambridge. His research is focused on problems at the intersection of quantum foundations and quantum information. See* http://mattleifer.info *for more details.*

Further Reading

Blog post with discussion of proof:
http://mattleifer.info/2011/11/20/can-the-quantum-state-be-interpreted-statistically/

The PBR paper:
M. Pusey, J. Barrett, T. Rudolph, (2011). http://arxiv.org/abs/1111.3328

For constraints on the size of the ontic state space see:
L. Hardy, *Stud. Hist. Phil. Mod. Phys*. **35**:267-276 (2004).
A. Montina, *Phys. Rev. A* **77**, 022104 (2008). http://arxiv.org/abs/0711.4770

For the early quantum computational complexity results see:
E. Bernstein and U Vazirani, *SIAM J. Comput.* **26**:1141-1473 (1997). http://arxiv.org/abs/quant-ph/9701001

For a fully rigorous version of the PBR+EPR nonlocality argument see:
N. Harrigan and R. W. Spekkens, *Found. Phys*. **40**:125 (2010). http://arxiv.org/abs/0706.2661

What increases when a self-organizing system organizes itself?

Charles H. Bennett

In one of the most important ideas from the 19th century, dating back to Darwin and Spencer, nonequilibrium boundary conditions, acting over geological time, are thought to have caused the biosphere to self-organize (see, for example, Figure 1). The idea remains controversial, having recently been ridiculed by creationists in their peanut butter video. A more humble example of self-organization is Sean Carroll's coffee cup equilibration experiment (see Figure 2), discussed in Scott Aaronson's article "The First Law of Complexodynamics," [Aaronson11] in the previous issue of this newsletter. The initial layered state and the final fully mixed state are each "simple," but the intermediate state, with coffee-rich and milk-rich tendrils along an irregular boundary, is "complex." A still more elementary example is provided by the one-dimensional reversible cellular automaton pictured in Figure 3 (p.5). Started from a simple initial condition at the left edge (periodic, but with a symmetry-breaking defect) it generates a deterministic wake-like history of growing size and complexity. (The automaton obeys a second order transition rule, a site's future differing from its past if and only if exactly two of its first and second neighbors, not counting the site itself, are black and the remaining two white in the present time slice.) But just what is it that increases when a self-organizing system organizes itself?

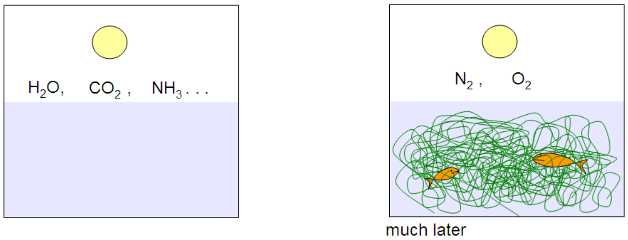

Figure 1. Self-organization of the biosphere.

This kind of organized complexity is not a thermodynamic potential like entropy or free energy. To see this, consider the possible transitions between a flask of sterile nutrient solution and a flask full of bacteria (Figure 4, p. 5). The transition from sterile nutrient to bacterial culture is allowed by the Second Law, but prohibited by a putative "slow growth law" that prohibits organized complexity from increasing too quickly, except with low probability. The same example shows that organized complexity is not an extensive quantity like free energy. Because a flask of nutrient with one seed bacterium can quickly turn into a bacterial culture, it must have nearly the same amount of organized complexity. On the other hand, its free energy is close to that of a flask of sterile nutrient.

Figure 2. A mixture of coffee and milk. Adapted from Sean Carroll's figure that appeared in Scott Aaronson's article, *The Quantum Times* **6**, 2 (2011).

The relation between universal computer programs and their outputs has long been viewed as a formal analog of the relation between theory and phenomenology in science, with the various programs generating a particular output x being analogous to alternative explanations of the phenomenon x. This analogy draws its authority form the ability of universal computers to execute all formal deductive processes and their presumed ability to simulate all processes of physical causation.

In algorithmic information theory the *Kolmogorov complexity*, or *information content* of a bit string x as defined as the size in bits of its *minimal program* x^*, the smallest (and lexicographically first, in case of ties) program causing a standard universal computer U to produce exactly x as output and then halt.

$$x^* = \min\{p\colon U(p) = x\}$$

Because of the ability of universal machines to simulate one another, Kolmogorov complexity is machine-independent up to an additive constant. Bit strings whose minimal programs are no smaller than the string itself are called *incompressible*, or *algorithmically random*, because they lack internal structure or correlations that would allow them to be specified more concisely than by a verbatim listing. Minimal programs themselves are incompressible to within $O(1)$, since otherwise their minimality would be undercut by a still shorter program. By

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contrast, any program p that is compressible is intrinsically implausible as an explanation for its output, because it contains internal redundancy that could be removed by deriving it from the more economical hypothesis p^*. In terms of Occam's razor, an s-compressible program is deprecated as an explanation of its output because it contains s bits worth of ad-hoc assumptions.

Kolmogorov complexity itself is not a good measure of organized complexity because it assigns high complexity to typical random strings generated by coin tossing, which intuitively speaking are trivial and unorganized. Accordingly many authors have sought a modified version of Kolmogorov complexity—also measured in entropic units like bits—to suitably formalize the kind of complexity that increases during self-organization, then decreases as the system decays to thermal equilibrium.

Figure 3. One-dimensional, reversible cellular automaton.

I will argue that scalar measures of complexity, particularly entropic ones, are inadequate for this purpose, and that a non-scalar complexity measure called logical depth, measured in units of computation time but essentially including algorithmic compressibility in its definition, is most suited to characterizing the kind of organized complexity that appears to increase, at least initially, in the three examples above.

The motivation for logical depth comes from a common feature of intuitively organized objects: the internal evidence they contain of a nontrivial causal history. If one accepts that an object's minimal program represents its most plausible explanation, then the minimal program's run time represents the number of steps in its most plausible history. To make depth stable with respect to small variations in x or U, it is necessary also to consider programs other than the minimal one, appropriately weighted according to their compressibility, resulting in the following two-parameter definition.

- An object x is called d-deep with s bits significance iff every program for U to compute x in time $< d$ is compressible by at least s bits. This formalizes the idea that every hypothesis for x to have originated more quickly than in time d contains s bits worth of ad-hoc assumptions.

Dynamic and static complexity, in the form of the parameters d and s, play complementary roles in this definition: d as the quantifier and s as the certifier of the object's nontriviality. Invoking the two parameters in this way not only stabilizes depth with respect to small variations of x and U, but also makes it possible to prove that depth obeys a slow growth law, without which any mathematical definition of complexity would seem problematic.

- A fast deterministic process cannot convert shallow objects to deep ones, and a fast stochastic process can only do so with low probability. (For details see Bennett88.)

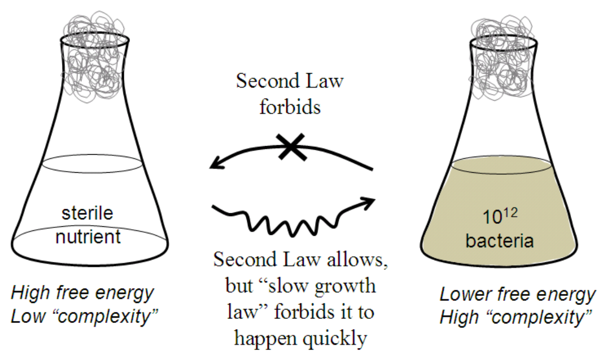

Figure 4. Complexity versus Free Energy

Returning to the pictures, in the Sean Carroll's coffee cup example (Figure 2 above), the intermediate state has a visibly complex pattern at the milk-coffee interface probably requiring a nontrivial computation to simulate. The macroscopically irregular structure, with interpenetrating milk-rich and coffee-rich tendrils, suggests a combination of turbulence and diffusion. (Diffusion alone would have been computationally easier to simulate, but would have generated only a smooth gradient, with Poissonian density fluctuations at a microscopic scale). The interface is logically deep to the extent that a nontrivial computation would be required to simulate how that structure could have arisen from a simple description. By contrast, the final equilibrium state of the coffee is logically shallow, despite its longer temporal history, because an alternative computation could short-circuit the system's actual evolution and generate the structure simply by calculating the thermodynamic equilibrium state under the prescribed boundary conditions. Informally speaking, the intermediate state is deep because it contains internal evidence of a complicated

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causal history, while the final state is shallow because such evidence has been obliterated by the equilibration process.

Logical depth addresses many infelicities and problems noted by Aaronson in the previous issue of this newsletter, where he tentatively defined the "complextropy" of *x* as the minimal program size for efficiently generating a probability distribution with respect to which *x* cannot efficiently be recognized as atypical.

- Depth does not impose an arbitrary rate of exchange between the independent variables of strength of evidence and degree of nontriviality of what the evidence points to, nor an arbitrary maximum complexity that an object can have, relative to its size. Just as a microscopic fossil can validate an arbitrarily long evolutionary process, so a small fragment of a large system, one that has evolved over a long time to a deep state, can contain evidence of entire depth of the large system, which may be more than exponential in the size of the fragment.
- It helps explain the increase of complexity at early times and its decrease at late times by providing different mechanisms for these processes. In Figures 2 and 3, for example, the depth increases steadily at first because it reflects the duration of the system's actual history so far. At late times, when coffee-milk distribution has become nearly uniform, or the cellular automaton has run for a generic time comparable to its Poincaré recurrence time, the state becomes shallow again, not because the actual history was uneventful, but because evidence of that history has become degraded to the point of statistical insignificance, allowing the final state to be generated quickly from a near-incompressible program that short-circuits the system's actual history.
- It helps explain why some systems, despite being far from thermal equilibrium, never self-organize. For example in Figure 1, the gaseous sun, unlike the solid earth, appears to lack means of remembering many details about its distant past. Thus while it contains evidence of its age (e.g. in its hydrogen/helium ratio) almost all evidence of particular details of its past, e.g. the locations of sunspots, are probably obliterated fairly quickly by the sun's hot, turbulent dynamics. On the other hand, systems with less disruptive dynamics, like our earth, could continue increasing in depth for as long as their nonequilibrium boundary conditions persisted, up to an exponential maximum imposed by Poincaré recurrence.
- Finally, depth is robust with respect to transformations that greatly alter an object's size and Kolmogorov complexity, provided the transformation leaves intact significant evidence of a nontrivial history. Even a small sample of the biosphere, such as a single DNA molecule, contains such evidence. Mathematically speaking, the depth of a string *x* is not much altered by replicating it, padding it with zeros or random digits, or passing it though a noisy channel (although the latter treatment decreases the significance parameter *s*).

The remaining infelicities of depth as a complexity measure are those afflicting computational complexity and algorithmic entropy theories generally.

- Lack of tight lower bounds: because of the open "P=PSPACE" question one cannot exhibit a system that provably generates depth more than polynomial in the space used.
- Semicomputability: deep objects can be proved deep (with exponential effort) but shallow ones can't be proved shallow. The semicomputability of depth, like that of Kolmogorov complexity, is an unavoidable consequence of the unsolvability of the halting problem.

The following observations can be made partially mitigating these infelicities.

- Using the theory of cryptographically strong pseudorandom functions one can argue (if such functions exist) that deep objects can be produced efficiently, in time polynomial and space polylogarithmic in their depth, and indeed that they are produced efficiently by some physical processes.
- Semicomputability does not render a complexity measure entirely useless. Even though a particular string cannot be proved shallow, and requires an exponential amount of effort to prove it deep, the depth-producing properties of stochastic processes can be established, assuming the existence of cryptographically strong pseudorandom functions. This parallels the fact that while no particular string can be proved to be algorithmically random (incompressible), it can be proved that the stochastic process of coin tossing produces algorithmically random strings with high probability.

I close with some comments on the relation between organized complexity and thermal disequilibrium, which since the 19th century has been viewed as an important, perhaps essential, prerequisite for self-organization. Broadly speaking, locally interacting systems at thermal equilibrium obey the Gibbs phase rule, and its generalization in

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Bennett, continued

which the set of independent parameters is enlarged to include not only intensive variables like temperature, pressure and magnetic field, but also all parameters of the system's Hamiltonian, such as local coupling constants. A consequence of the Gibbs phase rule is that for generic values of the independent parameters, i.e. at a generic point in the system's phase diagram, only one phase is thermodynamically stable. This means that if a system's independent parameters are set to generic values, and the system is allowed to come to equilibrium, its structure will be that of this unique stable Gibbs phase, with spatially uniform properties and typically short-range correlations. Thus for generic parameter values, when a system is allowed to relax to thermal equilibrium, it entirely forgets its initial condition and history and exists in a state whose structure can be adequately approximated by stochastically sampling the distribution of microstates characteristic of that stable Gibbs phase. Dissipative systems—those whose dynamics is not microscopically reversible or whose boundary conditions prevent them from ever attaining thermal equilibrium—are exempt from the Gibbs phase rule for reasons discussed in Ref. BG85, and so are capable, other conditions being favorable, of producing structures of unbounded depth and complexity in the long time limit. For further discussion and a comparison of logical depth with other proposed measures of organized complexity, see Ref. Bennett90.

Charles H. Bennett *has spent the past 40 years at IBM Research where he has studied many aspects of the physics of information processing. He is known for his work on reversible computing and Maxwell's demon, quantum cryptography and quantum teleportation, and the theory of entanglement and entanglement-assisted communication. His has long been interested in applying algorithmic information and computational complexity to characterize self-organization and understand its thermodynamics. He was the first chair of the APS Group on Quantum Information.*

References and links

Links:
Herbert Spencer biography: http://en.wikipedia.org/wiki/Herbert_Spencer
The peanut butter video: http://www.youtube.com/watch?v=FZFG5PKw504
Gibbs' phase rule: http://en.wikipedia.org/wiki/Gibbs'_phase_rule

References:
[Aaronson11] S. Aaronson, "The First Law of Complexodynamics," *The Quantum Times* **6**, 1; http://www.aps.org/units/gqi/newsletters/upload/vol6num2.pdf

[Bennett88] C.H. Bennett, "Logical Depth and Physical Complexity," in *The Universal Turing Machine – a Half-Century Survey*, R. Herken, ed., Oxford University Press (1988); http://bit.ly/nh0bra

[Bennett90] C.H. Bennett, "How to Define Complexity in Physics, and Why," in *Complexity, Entropy, and the Physics of Information, SFI Studies in the Sciences of Complexity, vol. VIII*, W.H. Zurek, ed., Addison-Wesley (1990); http://web.archive.org/web/20061015234424/http://www.research.ibm.com/people/b/bennetc/bennettc19903b272b10.pdf

[BG85] C.H. Bennett and G. Grinstein, "Role of Irreversibility in Stabilizing Complex and Nonergodic Behavior in Locally Interacting Discrete Systems," *Physical Review Letters* **55**, 657-660; http://www.de.ufpe.br/~toom/others-articles/engmat/BEN-GRI.pdf

Complex-o-dynamics or complex-*i*-dynamics?

In our previous issue, Scott Aaronson used the term 'complexodynamics.' I do not know if that term was original to that particular article or if it cropped up at the FQXi meeting in August. Either way, Charlie Bennett continued the usage of the term in his article in this issue. I am going to play the role of David Mermin here (who objects to the term 'qubit' in favor of 'Q-bit') and object to the word 'complexodynamics' on lexicographical grounds. The use of the 'o' as a bridge between 'complex[ity]' and 'dynamics' is clearly borrowed from the term 'thermodynamics' where it serves as a bridge between 'therm[al]' and 'dynamics.' The first vowel of 'thermal' that gets dropped is an 'a' and, phonetically, an 'o' works well as a replacement (there is likely some semi-official rule about this that my father [a retired English teacher] would know, but this is English so rules tend to be arbitrary anyway). It seems more natural to me to instead use an 'i' since it better captures that first vowel being dropped when merging the two words. So, henceforth, I will be lobbying – strongly – in favor of the phonetically better choice 'complexidynamics.'

–Ian T. Durham, Editor

Letter from the Chair-elect

The exciting advances in quantum information science continue to spur the growth of GQI. Since its founding in 2005, GQI has been the fastest growing of the APS Topical Groups, and surely one of the most vibrant. We now have over 1100 members, and more than 600 student members, by far the largest student percentage of any APS unit. Our current rate of growth projects to 1500+ members by 2016, more than enough to establish an APS Division of Quantum Information.

Another way to monitor the development of our field is to track GQI participation in the APS March Meeting. One of my responsibilities as Chair-Elect is to oversee the quantum information sessions at the March Meeting, a job I accepted with trepidation after witnessing the fantastic job done by Chris Fuchs, my predecessor. But I need not have worried. For the 2012 Meeting (in Boston February 27 through March 2) 410 talks were submitted to the quantum information sessions, up more than 25% from last year, and sufficient to fill 30 Focus and Contributed Sessions.

In addition, GQI will sponsor or co-sponsor these seven exciting sessions of invited talks:

A2. Teaching quantum information science at liberal arts colleges (Schumacher, Westmoreland, Wootters, Bernstein, Galvez)
D44. Topological quantum computing with Majorana Fermions (Alicea, Sau, Kouwenhoven, Akhmerov, Brouwer)
J3. Quantum computing with superconducting circuits (Siddiqi, Wilson, Steffen, Mariantoni, Reed)
P10. Quantum simulations (Spielman, Blatt, Girvin, Hafezi, Altman)
Q46. Quantum information processing in diamond (Jelezko, Fu, Harris, Bernien, Bassett)
V10. Quantum entanglement in many-body systems (Polzik, Verstraete, Leibfried, Wen, Aaronson)
W46. Silicon spin qubits: relaxation and decoherence (Simmons, Gyure, Jiang, Witzel, Hu)

And you won't want to miss the **GQI business meeting on Tuesday at 5:45**, where you can meet and greet your fellow quantum informationists.

The March Meeting provides a valuable opportunity for quantum information enthusiasts to exchange ideas with the broader physics community, and to convey the excitement of our field. Naturally, since the March Meeting is dominated by the condensed matter physicists, the interface of quantum information with condensed matter gets special emphasis, but contributions in all areas of quantum information science are encouraged. GQI's current Vice-Chair Daniel Lidar will take charge of the quantum information sessions for the 2013 March Meeting in Baltimore, and I am sure he will welcome your suggestions on how to make next year's meeting even better.

Thanks so much to all of you who have helped with organizing GQI's participation in this year's March Meeting, especially Invited Session organizers Eugene Demler, Ian Durham, Mark Eriksson, Ronald Hanson, John Martinis, and Gil Refael; Focus Session organizers David Awschalom, Alexandre Blais, Giulio Chiribella, Thaddeus Ladd, Roman Lutchyn, and Matthias Steffen; and Session Sorters Lev Bishop, Qiuzi Li, Ben Palmer, Charlie Tahan, Shuo Yang, and Xin Wang. Because of your efforts we will all have a blast in Boston!

–John Preskill, Chair-elect

New APS GQI Fellows

Congratulations to the newest APS (GQI) Fellows!

Edward Farhi: "For his seminal discoveries of new quantum algorithms and quantum computational paradigms, in particular the quantum walk and quantum adiabatic methods."

Raymond Laflamme: "For his visionary leadership in the field of quantum information science, and for his numerous fundamental contributions to the theoretical foundations and practical implementation of quantum information processing, especially quantum error correction and linear optical quantum computing."

Jeremy O'Brien: "For his seminal contributions to quantum optics, in particular for founding contributions to the field of integrated quantum photonics and its applications to quantum information processing and quantum metrology."

John Smolin: "For his profound contributions to the elucidation of phenomena and techniques central to our current understanding of quantum information theory."

Howard Wiseman: "For his seminal contributions to the quantum theory of measurement, particularly to the formulation of continuous measurement, feedback, and control."

Paolo Zanardi: "For his visionary leadership in the field of quantum information science, and for his numerous fundamental contributions to the theoretical foundations and practical implementation of quantum information processing, especially quantum error correction and linear optical quantum computing."

Bits, BYTES, *and Qubits*

QUANTUM NEWS & NOTES

The end of complementarity?

As Matt Leifer described in the above article, "PBR, EPR, and all that jazz," the anti-realist or neo-Copenhagen point of view on quantum theory takes the quantum state not as representing knowledge about an underlying reality, but rather as representing knowledge about the consequences of measurements that might be made on the system. One implication of this is that it is impossible to simultaneously measure both the wave and particle natures of quantum states since doing so would amount to simultaneously possessing both partial and complete information about a particular aspect of a quantum state which is – or should be! – absurd (this assumes that the wave nature manifests itself in a statistical manner). This, of course, is Neils Bohr's famous Principle of Complementarity.

One way in which wave-particle duality is demonstrated is with a two-beam interferometer. For a beam of very low intensity that essentially delivers photons one-at-a-time, the presence of interference is taken to imply that each photon traverses both arms of the interferometer simultaneously, thereby demonstrating its wave nature. However, if either of the arms of the interferometer are observed, the photon's state appears particle-like. This is akin to the classic two-slit experiment in which particle detectors are positioned at the slits; when the detectors are activated, the interference pattern disappears.

Those who are uncomfortable with that result have proposed a number of explanations including that the photons somehow know about the detectors ahead of time (hidden variables!). John Wheeler ultimately put the kibosh on that thirty years ago when he proposed a delayed choice experiment that switched from a "wave-like" setup to a "particle-like" setup (or vice-versa) as an individual photon was in flight. This experiment was realized in 2007 by Alain Aspect's group at Orsay (V. Jacques, E Wu, F. Grosshans, F. Treussart, P. Grangier, A. Aspect, and J.-F. Roch, "Experimental Realization of Wheeler's Delayed-Choice Gedanken Experiment," Science 315, 966 (2007)). The experiment actually *removed* one arm of the interferometer after a given photon had begun its flight. The problem here is that one could argue that the *classical* act of removing an entire arm of the beamsplitter introduces decoherence or other such effects into the system. In other words, it wasn't necessarily clear *why* the state switched its nature from wave to particle or vice-versa: was it due to classical or quantum effects?

Radu Ionicioiu, now at the Institute for Quantum Computing in Waterloo, Canada, and Daniel Terno of Macquarie University in Sydney, Australia have recently proposed a *quantum* method for achieving the same result, leaving no doubt as to the source of the state's change. They have proposed that the detector itself be a quantum "device," e.g. an atom in a cavity or a micro-mirror placed on a cantilever, such that the detector can be in a superposition of "wave detection" and "particle detection" states. Essentially this means that both the wave and the particle experiments can be implemented at once, thus indefinitely delaying the choice of wave versus particle. In other words, the photon can be "observed" at one of the detectors and yet still exist in a superposition of wave and particle states. It's only when the observer measures the state of the actual quantum *device* that the photon can be deemed a wave or a particle. Thus it appears that this provides a way around complementarity by allowing the simultaneous measurements of the two states.

Of course, one could argue that this merely moves the problem from the photon to the measurement device; what if we add a second device designed to measure the state of the first device? An anti-realist or neo-Copenhagen proponent might argue that we, as (very classical) human beings, can still never perform such an experiment without complementarity forcing a result at *some* level, even if it isn't at the level of the photon.

Either way, the new *gedankenexperiment* by Ionicioiu and Terno provides some food for thought for both theorists and experimenters alike.

–ITD

Q+ at Google+

Google+ (http://plus.google.com) is the hot new property in the social media space. Since it started in the second half of last year it has attracted a surprisingly large number of users from the quantum information community. There is a quant-ph circle maintained by Dan Browne, to which people may post links to arXiv articles that they find interesting and start discussions about them. This has become the best place for online discussion of quantum preprints since the demise of Dave Bacon's SciRate last year.

One of the most exciting features of Google+ is hangouts, which provide an ad-hoc way of holding Skype-like video chats with multiple participants. This has tremendous potential as a medium for research discussion. Daniel Burgarth and I have been organizing online seminars on quantum information and foundations using them for the past few months, which we call Q+ hangouts. Previous speakers have included Adrian Kent, Andreas Winter, Matt Pusey and Martin Plenio. The next talk will be on 24th January at 14:00 GMT and features Huw Price speaking about the possibility of retrocausality in quantum theory.

Continued on next page

News, continued

Participation is open to everyone. All you need is a computer with a webcam and a web-browser, and a Google+ account. For further information, follow the Q+ page on Google+ (http://bit.ly/wGBZUA) or see our webpage (http://qplus.burgarth.de).

Since Google+ is new, there are currently a few restrictions on hangouts, the most important of which is that they are restricted to ten participants. Because of this, we prioritize people who are willing to share their connection with others, e.g. by displaying the talk on a projector in a seminar room. If you are going to do this then you may reserve a spot in advance by commenting on the announcement on the Q+ page. The remaining spots are assigned on a first-come, first-served basis on the day of the talk.

–Matt Leifer

APS Topical Group on Quantum Information

Image credit

The image depicted on page 1 is of Frederick Childe Hassam's *Boston Common at Twilight* (1905).

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Contributions

Contributions from readers for any and all portions of the newsletter are welcome and encouraged. We are particularly keen to receive

- **op-ed pieces and letters** (the APS is *strongly* encouraging inclusion of such items in unit newsletters)
- **books reviews**
- **review articles**
- **articles describing individual research** that are aimed at a broad audience
- **humor** of a nature appropriate for this publication

Submissions are accepted at any time. They must be in electronic format and may be sent to the editor at idurham@anselm.edu. Acceptable forms for electronic files (other than images) include LaTeX, Word, Pages (iWork), RTF, PDF, and plain text.

Editorial policy

All opinions expressed in *The Quantum Times* are those of the individual authors and do not represent those of the Topical Group on Quantum Information or the American Physical Society in general.

Quantum Error Correction 2011 (QEC11) - Notice

Thanks to the efforts of Kristen Pudenz most of the lectures are now online, in both ppt/pdf and video formats: http://qserver.usc.edu/qec11/program.html. The videos are large files and you may have to save them before you can play them.

Program Announcement

Control of Complex Quantum Systems

Kavli Institute for Theoretical Physics
University of California, Santa Barbara

January 7 – March 29, 2013

Applications are now being accepted for the program. There will also be a conference associated with this program, entitled *"New Directions in the Quantum Control Landscape"*, to be held from February 25 – March 1, 2013. A summary and the latest information about the program can be found online at http://www.kitp.ucsb.edu/activities/dbdetails?acro=qcontrol13. We encourage you to inform others who might be interested in participating in the program. To apply, please go to the web page above, and click on the **above link**. **Application deadline: January 30, 2012**.

Organizers:

- Tommaso Calarco (*Innsbruck*)
- Ivan Deutsch (*New Mexico*)
- Gerard Milburn (*Queensland*)
- Birgitta Whaley (*Berkeley*)

The Kavli Institute for Theoretical Physics
University of California, Santa Barbara