All Is (Q-)Number

In a world full of headlines touting 'the latest theory of everything', the most valuable unturned stone might be the theories we have had for a century. We just need the courage to do as Sam Kuypers does and take them seriously.

BY LOGAN CHIPKIN

Image by Amaro Koberle

Three major influences drew Conjecture Institute Fellow Sam Kuypers to physics as a teenager: a high school course, Richard Feynman videos, and his father.

"For some reason, my dad had loads of in-depth knowledge about the theory of circuits and electronics," Sam recalls. "He also knew a great deal about classical mechanics, and almost anything else that came up in secondary-school physics. Somehow he had retained nearly all of it over the years. So I'd tell him about my physics class that day, and the two of us would talk about it for hours. Talking with him was much more interesting than the classes themselves; he had a way of bringing the material to life. Our conversations made me realize how valuable one-on-one interactions are for learning."

Sam fell in love with the counterintuitive facts that Newtonian mechanics told us about the world. That objects launched from the ground would slow down until they had a vertical velocity of literally zero for just a moment at the top of their trajectory struck Sam as both bizarre and fascinating. Moreover, he was not only captivated by the *facts* and *theories* of physics, but also by the fact that we could *know* them—hinting at his future passion for epistemology, the philosophy of knowledge.

"When I was young and new to physics, I was blown away by the fact that, even if you didn't know the particular path that a projectile took, you could know that it would hang still in the air for just a moment—that is, its vertical velocity must be zero at some point, unless it went off into space," Sam recalls. "It seemed like a bold claim to make. But it is, of course, true."

Sam would go on to attend the University of Amsterdam, where he would earn a bachelor's degree in physics and astronomy and a master's in theoretical physics. During this time, his primary interest was condensed matter theory, the study of how vast numbers of particles conspire together to give rise to emergent phenomena like superconductivity and magnetism.

Sam's early interest in the subject planted the seeds of his eventual fascination with quantum theory, which has come to define much of his work.

"Condensed matter theory is basically the theory of macroscopic systems—of things like magnets, metals, and semiconductors," Sam says. "I thought it was boring at first because it didn't seem fundamental, but the more I delved into it, the more interesting it became. I realized that, although the systems described by the theory are very large, most of their properties are quantum mechanical. This led me to puzzle over an odd discrepancy—people would say that only the microscopic world was described by quantum mechanics, yet we clearly have quantum mechanical descriptions of macroscopic systems. So I became more interested in quantum foundations, since this widely accepted contradiction, inherent to conventional explanations of quantum theory, made no sense to me."

In his final year as an undergraduate, Sam would read physicist David Deutsch's books, *The Fabric of Reality* and *The Beginning of Infinity*, both of which argue for the Many-Worlds interpretation of quantum mechanics (also called 'Everettian quantum theory'). The books completely changed Sam's worldview, not least because he saw that there was actually a solution to many of the issues he had been noticing in quantum mechanics.

"I was totally persuaded by everything, but I had my doubts about Everett," Sam says. "So I read Everett's long thesis to check the math, and it worked! So I was persuaded, and now it's one of the main things I work on."

With his interest in quantum foundations firmly in place, Sam applied for a PhD position at the University of Oxford, in physicist Vlatko Vedral's group. There, he would apply Everettian quantum theory to a variety of open problems in the foundations of physics, such as time travel, the quantum theory of time, and the so-called *Heisenberg picture* of quantum theory.

"I wanted to see how far you could push the Everettian model in all of these directions," Sam says.

In Sam's thesis, *Developments in unitary quantum theory*, he:

1. Showed that Everettian universes are local, like bubbles that grow but are independent of their exterior (more technically, he demonstrated that Everett's relative-state construction was viable in the Heisenberg picture),
2. Identified and articulated a principle implicit in quantum theory: that the descriptors of physical systems are q-number valued (rather than c-number valued—see Box 1),
3. Demonstrated that it is possible to express quantum theory without invoking classical notions of time in the Heisenberg picture, and
4. Developed the theory of unorthodox quantum theory, which relinquishes a problematic assumption in orthodox quantum theory called the *commutation constraint*.

Much of this work would live on in Sam's earliest scientific papers (see Boxes 1 and 2 for details).

What unifies Sam's thesis and corresponding papers is that they all take quantum theory seriously as a fundamental description of reality. Even though the Schrödinger and Heisenberg pictures make equivalent predictions, Sam took the latter to be more fundamental, and that, therefore, problems that had been solved *only* in the Schrödinger picture needed solving in the Heisenberg picture, too. And even though collapse models of quantum theory 'worked' for most practical purposes, only Everett's relative-state construction and corresponding Many-Worlds interpretation actually made sense of quantum theory. Combining these two explanatory improvements to traditional views of quantum theory—the Heisenberg picture over the Schrödinger picture and Everett's relative-state construction over collapse models—Sam solved problems in physics' theoretical edifice for which the older perspectives on quantum theory never could.

BOX I

Quantum Time and the Fundamental Principle of Quantum Theory

In any classical theory, such as Newtonian mechanics, Maxwell's (pre-quantum) theory of electromagnetism, or Einstein's general relativity, physical quantities such as position, momentum, electric charge, or the metric tensor are all characterized by *c-numbers* (or *c-number descriptors*), which are the commonsensical, single-valued numbers (or functions more generally). Critically, c-numbers *commute* with each other, which means that the order in which you measure them does not matter. For example, it does not matter whether you first measure the velocity of a car and then its position or vice versa—the order in which you make the measurements will not change the numbers you read for the car's velocity and position. At each moment in time, the car has only one possible value of velocity and position. The same goes for a classical electromagnetic system or a system described by general relativity.

One of the hallmarks of quantum theory is a radical departure from the intuitive logic of c-numbers. The theory tells us that all physical quantities (also called *observables*) are characterized by *q-numbers* (or *q-number descriptors*), which are *not* single-valued and whose order of measurement *does* matter in general. Mathematically, q-numbers correspond to *matrices* or *operators*. Whereas the velocity of an object in Newtonian mechanics might be 10 m/s, the velocity of an object in quantum mechanics might be 9 m/s, 10 m/s, and 11 m/s all simultaneously (see Box 2 for a discussion on what this means). Moreover, the order of measurement matters for quantities described by q-numbers. For example, imagine you prepare many instances of an electron, all prepared in the same initial state. For half of them, you measure their position first and their velocity second, and vice versa for the other half. Because the order of measurement matters, you will have different statistical outcomes for each subgroup of electrons.

According to Sam, the fact that all physical systems in quantum theory are characterized by q-numbers is *the fundamental principle of quantum theory*.

The Pythagoreans made a valiant attempt at describing the world and were right to consider it a principle that “All is number”, i.e. that the physical world ought to be describable by numbers. At the same time, their own parochial conception of numbers led them to conclude that only rational numbers were valid descriptors and that, for instance, irrational numbers (numbers that cannot be expressed as the ratio of two integers) were somehow illegitimate.

Many refinements of the Pythagoreans’ basic thesis have taken place over the course of thousands of years, as mathematicians and physicists have discovered ever broader classes of numbers that are both internally consistent and capable of describing the physical world.

Sam’s refinement is that, in light of his proposed fundamental principle of quantum theory, the Pythagorean mantra “All is number” should be replaced by: “All is q-number.” According to Sam, the fact that all physical systems in quantum theory are characterized by q-numbers is not merely a feature of the theory’s mathematical formalism, but its fundamental physical principle.

Until 1983, there had been an awkward violation to this principle—time. All of a system’s q-number-described observables had been assumed to evolve relative to a c-number-described time, ruining the universality of Sam’s principle. Moreover, this c-number time is necessarily unphysical, as it has no physical relationship with any of a system’s q-numbers. Instead, “This c-number time is…an unphysical backdrop against which quantum systems can change. In fact, c-number time is all but identical to Newton’s absolute time…”

This problematic c-number time may be contrasted with *clock time*, which is the straightforward and commonsensical measurement of the change of a clock. While c-number time is thought to ‘flow’ uniformly and independently of the behavior of quantum systems as a kind of god-like background of the universe, clock time is a definite, physical component of a system and, as Page and Wootters had shown in 1983, can be characterized by q-numbers.

As Sam writes, "To make clear the distinction between clock time and c-number time, consider a hypothetical situation in which all physical systems in the universe suddenly 'freeze' relative to c-number time. Clocks are physical systems and would be stationary during this 'freeze', which makes the 'freeze' and its duration completely undetectable to any observer in the universe. C-number time must therefore be just as unmeasurable as the duration of the 'freeze'."

The Page and Wootters resolution of the conflict between the fundamental principle of quantum theory and c-number time is limited by the fact that they developed their model using the *Schrödinger* picture of quantum mechanics, rather than the *Heisenberg* picture. While both formulations yield the same predictions, they are conceptually distinct. Moreover, Sam and others argue that the Heisenberg formulation is more fundamental—for example, only the Heisenberg picture makes explicit quantum theory's consistency with the principle of locality (the idea that systems can only affect other systems in their immediate vicinity). Therefore, one could argue that, while Page and Wootters had successfully excised c-number time from the *Schrödinger* formulation of quantum mechanics, perhaps it could not possibly be excised from the *Heisenberg* formulation. In that case, perhaps Sam's fundamental principle of quantum theory would be mistaken, after all.

Sam went on to demonstrate that, in fact, it is possible to replace c-number time with clock time in the Heisenberg picture. All of the conceptual and mathematical issues that a classical conception of time had brought to the quantum world could indeed be done away with.

In the conclusion of his paper, Sam drew attention to striking similarities between the clocks in his version of the Page-Wootters model and some fundamental properties of *spacetime manifolds*—mathematical objects that describe the geometry of regions of the universe in general relativity. He conjectures that the similarities are not a coincidence and that, in fact, "the properties of a [spacetime] manifold can be formulated in terms of q-numbers." Sam's conjecture, if true, drastically constrains the space of viable candidates for the long-sought solution to the problem of unifying general relativity and quantum mechanics.

Nor was it enough for Sam to think of quantum theory as 'just' an equation that described the evolution of physical systems over time —his fundamental principle of quantum mechanics is a deeper characterization about what the theory is all about than any single algebraic equation could possibly be. As he writes, "'quantum theory' is better thought of as a collection of theories that comply with this fundamental principle…The reason why quantum theory is better thought of as a set of principles is that it does not describe particular systems…Quantum theory is not about any of those systems in particular [atoms, photons, superconductors, quantum computers], but about all of them—or rather, it is about what kinds of theories can describe physical objects."

Sam had been quite fortunate to earn his PhD under Vlatko, who had been laissez-faire with respect to what sort of research Sam could or could not pursue. Even so, the university itself had a different, more paternalistic philosophy.

"There was a stark contrast between Vlatko's wonderful willingness to just let me work on anything I wanted and Oxford's policies," Sam remembers. "For example, every few months I'd have to regularly justify my research to a person in charge of research students. These online check-ins gave me mild anxiety—after all, what if I hadn't made enough progress since our last meeting to satisfy him? Or what if he didn't approve of what I had been working on?"

BOX 2

Everettian Relative States in the Heisenberg Picture

The so-called 'collapse postulate' was introduced by Werner Heisenberg in 1927, formalized by John von Neumann in 1932, and has been a hallmark in mainstream textbooks, university courses, and research groups ever since. The idea is that the principles and equations of quantum mechanics apply to a system *until* it is observed or measured. Before then, quantum mechanics seems to imply that the system has many values at once for its observables—for example, it would not have a single value for its position but rather a series of well-defined values, all equally real or equally probable. Once the system is observed or measured, though, the system 'collapses' such that only one of its many possible outcomes remains—the one that is observed.

The collapse postulate does not sit comfortably with the other principles of quantum mechanics. Not only do the rest of the principles already cohere to form an explanatory theory (i.e., the collapse postulate is not needed to make the theory 'work'), but the collapse postulate in fact *adds* problems that had not existed: what counts as a measurement? How do we square the continuous, deterministic, and reversible nature of quantum theory's central equation with the collapse postulate's introduction of instantaneity (collapse takes no time to occur), indeterminism (whichever outcome the system collapses to is intrinsically random), and irreversibility?

Why ought we insist on collapse at all?

In his 1957 PhD thesis, Hugh Everett III considered what the world would be like if quantum theory was a truly universal theory, one that applied at all scales and whose equations did not collapse upon measurement.

As Sam and David Deutsch put it, "The arbitrariness, non-locality, vagueness, inelegance and anthropocentricity of this supposed exception [measurement events] has caused many misconceptions and confusions both in theoretical physics and in philosophy, despite the work of Everett (1973), including his relative-state construction, which eliminated the exception."

Consider a particle that has been carefully prepared such that, should a scientist measure its spin, quantum theory tells us that he will measure ‘spin up’ with 50% probability and ‘spin down’ with 50% probability. Collapse models would describe the particle *before* having been measured as being in a superposition of the two possibilities. Upon measuring the particle as being in the ‘spin up’ state, collapse models would say that the superposition has collapsed and that the 50% probability of the particle being in the ‘spin down’ state has utterly disappeared—there is only the scientist, his measuring device, and the particle in its ‘spin up state’.

Everett’s analysis drops the collapse assumption altogether. Rather than insist that the scientist and his measurement apparatus are ‘too macroscopic’ to be quantum objects, he takes quantum theory to be a universal theory of Nature: just as the particle exists in a superposition of ‘spin up’ and ‘spin down’, so do the scientist, the measurement apparatus, and every other physical system in reality.

Everett realized that the particle does not collapse into either ‘spin up’ or ‘spin down’. Instead, half of the copies of the scientist measure ‘spin up’, while the other half measure ‘spin down’. So, after the measurement event, the state of the particle is ‘spin up’ *relative* to the state of the scientist being ‘measured ‘spin up’’ and the state of the particle is ‘spin down’ *relative* to the state of the scientist being ‘measured ‘spin down’’. Naturally, Everett called this scheme the *Relative State Formulation*.

As Sam writes, “His primary technical innovation was to analyse quantum measurement processes by treating not only the system being measured but also the measuring apparatus or instrument (or *measurer,* for short) jointly as [an] evolving quantum system.”

The implication was clear—reality consists of a mindbogglingly large number of branches (or universes, or worlds) that are constantly splitting and differentiating from each other (they occasionally interact as well, but such processes do not concern us here).

Everett's advisor, John Wheeler, encouraged Everett to heavily edit down his consensus-defying thesis, as Wheeler was concerned over the physics community's reaction. It would not be until 1973 that Everett's uncut version saw the light of day, when Bryce DeWitt included it in his anthology, *The Many-Worlds of Quantum Mechanics*. It was DeWitt, not Everett, who would bring the phrase 'Many-Worlds' to the fore.

While Everett's construction and its implications have solved a host of problems that the collapse postulate had introduced (and then some), until 2020 all such work had been confined to the Schrödinger formulation of quantum mechanics. The logic of the situation is similar to that of quantum time (see Box 1): if Everett's construction could *not* be formulated in the more fundamental Heisenberg picture, then perhaps the Everettian approach and its implications of many worlds were not viable in the first place.

In 2020, Sam and David Deutsch successfully formulated Everett's relative-state construction in the Heisenberg picture. Not only is their formulation explicitly local (as one would expect, since Heisenberg quantum mechanics is local), but the branching of universes occurs at the speed of light or less (also as one would expect if Einsteinian relativity and the Many-Worlds picture of reality are to one day unify).

Academia's Boundary Conditions

After graduating with his PhD, Sam acquired a postdoctoral position in Lugano, Switzerland, working under quantum information scientist Stefan Wolf. Conjecture Institute Fellow Charles Bedard had been working under Wolf at the time, and he had gladly helped to earn Sam the position. While in Lugano, Sam would continue his work on the quantum theory of time, co-authoring a second paper on the subject alongside Simone Rijavec titled "*Measuring time in a timeless universe*".

“It was a really nice group, and I enjoyed my many discussions with Charles,” Sam recalls. “I was able to continue working on problems that I was interested in.”

Following his time in Lugano, Sam took a second postdoctoral position under quantum information scientist Gilles Brassard at the Université de Montréal. It was here that he became close with another Conjecture Institute Fellow, Paul Raymond-Robichaud, who lived nearby.

“We saw each other quite a lot,” Sam says. “And he persuaded me that mathematics was not taken seriously enough by physicists. As a whole, physicists tend to use mathematics rigorously enough to get by, but Paul explained to me why physics would benefit from holding their work up to the standards of mathematicians when developing their proofs and theorems. Ever since, I've tried to do exactly that in my work.”

Sam was not merely persuaded by Paul's general arguments, but also by Paul's own work on formalizing the notion of local-realism. Sam and Conjecture Institute Fellow Maria Violaris are now applying Paul's formulae to the physics of information. In particular, they are taking both Paul's notion of local-realism and the constructor theory of information to solve problems having to do with differences between locally accessible information and locally *in*accessible information.

Paul's influence on Sam would also be felt in Sam's chapter contribution to Alyssa Ney's compendium, *Local Quantum Mechanics: Everett, Many Worlds, and Reality*, which he also wrote during his time in Canada. His chapter, ‘Restoring Locality: The Heisenberg Picture as a Separable Description of Quantum Theory’, explains how local realism is respected in quantum theory, despite appearances and the popular consensus. Something of a review, Sam walks the reader through the historical context of the problem, how it was eventually solved by Deutsch and Patrick Hayden in 2000, and Paul's original contributions a couple of decades later.

Throughout his academic career, Sam experienced pressure by academic bureaucracy and funders alike to stick to a preset list of research topics. Any public funding he received during that time came with an expectation that he would satisfy some particular goal. But the questions Sam asks in his research do not yet have known solutions—that is why he pursues them in the first place! And if the solution cannot be known before the question is pursued, then neither can any arbitrary goal.

For example, Kuypers and Deutsch successfully provided a local account of branching using the Heisenberg picture, allowing them to describe universes that exist at remote locations from one another as separate systems with independent dynamics. But, strictly speaking, whether such a description was possible was not known beforehand, and so nobody could have known how this research would pan out. Conceivably, no local description of branching existed, in which case demonstrating *that* could itself have become a research project, which would have opened up further problems to work on. For example, it could have laid bare a fundamental discrepancy between the Schrödinger and Heisenberg pictures, in that in this hypothetical scenario one would support the relative-state construction while the other would not. This discrepancy would itself demand explanation.Now, this entire sequence of events would have been genuine progress in fundamental physics—and yet, most criteria that a funder would have attached to their funding of Sam, or guidelines insisted upon by the university system, could not have possibly been satisfied by both this outcome and the outcome that Sam *actually* achieved.

A New Quantum Mechanics: Textbook and Application

Since Sam became a Conjecture Institute Fellow in 2025, he has so far pursued two main projects.

The first is that he has continued to co-write a much-needed textbook on quantum mechanics alongside Deutsch and Conjecture Institute Senior Scientist Chiara Marletto. The Heisenberg picture and the Everett interpretation are both drastically underappreciated in the halls of academia, yet they have been and will continue to be vital for making progress in fundamental physics. The overwhelming majority of quantum mechanics textbooks downplay the Heisenberg picture and equivocate on the Everett interpretation at best and endorse an instrumentalist view of quantum physics at worst. They also tend to use unnecessarily complicated examples such as, say, the hydrogen atom and harmonic oscillators that require the reader to grok concepts and mathematical superstructures that are not intrinsic to the principles of quantum theory. Imagine if our best textbook on evolutionary theory today was written before the revolution of the selfish gene model, or if our best textbook on special relativity was written before the Minkowski spacetime was invented. That is precisely where we are with respect to quantum mechanics textbooks—there is scope for an update. To that end, Deutsch, Marletto, and Sam are writing a quantum mechanics textbook that fully incorporates the latest developments on the Heisenberg picture, the Everett interpretation, and quantum information theory.

Sam's recent preprint, *"Preserving Symmetry: Spontaneous Symmetry Breaking through Decoherence"*, was written during his time as a Conjecture Institute Fellow. As is the theme in so much of his research, Sam addressed a longstanding problem in quantum physics by looking at it through a Many-Worlds lens. In condensed matter theory, the field in which Sam began his research career, there is a conventional explanation for how solid objects obtain a definite position. Solids are 'translationally symmetric'–-when considered in isolation, they have the same energy regardless of where in space they are positioned; due to the physics of symmetries, this precludes them from being localised at any particular location, requiring them instead to be in a superposition that is spread out over all of space. Yet this is not how actual objects like tables and chairs seem to behave: they occupy definite locations.

The conventional solution is to introduce a classical environment that pins the system to a particular location. In the conventional account, known as spontaneous symmetry breaking, this classical environment is a mathematical artifact that is later removed by hand once the symmetry has been broken. Scientific realists might therefore object that the classical environment is doing real work, even if it is later brushed under the carpet.

As David Wallace had previously shown, the environment can instead be treated as a quantum system, restoring the symmetry so that the environment and the system are jointly completely spread out over space. Yet in different branches of the multiverse, the symmetry appears to be broken: a system can have a definite position in a particular universe *relative* to a quantum environment. Sam's contribution was to develop a specific model of this for translational symmetry and derive experimental signatures that distinguish the conventional account from the fully quantum one.

"What Wallace—and, separately, Zeh—showed is that you can have your cake and eat it too," Sam says. "We can preserve the symmetry at the level of the multiverse while breaking it within branches. This is a natural solution to the problems with the conventional account, but it requires both a realist interpretation of physics, in which the mathematical artifacts correspond to something real, and the Many-Worlds interpretation, because the whole description hinges on the multiverse being taken seriously. We need the other branches—the ones that we don't see—to restore the symmetry."

"It tackles a more conventional problem than my previous papers, which is a good thing to do every once in a while," Sam says. "It's still Many-Worlds, and I hope that it reaches a broad audience and maybe plants some Everettian seeds."

It was one of the most fun papers that Sam has ever written. "It helped that, as a Conjecture Institute Fellow, I didn't have to worry about fitting my work into exactly this or that bucket. Traditional academia had never granted me such creative freedom."

The Courage to Take Our Existing Principles Seriously

One of the most famous outstanding problems in physics is the clash between quantum mechanics and general relativity, the theory of spacetime, gravity, matter, and interactions between them. Each is a beautiful, deep, and wide explanation in its own right, and, despite contradicting each other, each can be used without referencing the other in many contexts. For example, the physics of planetary motion can be modeled by general relativity without considerations of quantum mechanics, and the trajectory of an electron in an atom can be modeled by quantum mechanics without considerations of general relativity. Yet there are physical phenomena whose behavior cannot be explained by just one or the other theory—events such as the Big Bang, and objects such as black holes, are dominated by *both* gravity and by quantum phenomena such as interference and superposition. Until we unify these two pillars of fundamental physics, then, much of reality is necessarily left unexplained.

Now, much of the effort that has gone into trying to marry quantum theory with general relativity has taken most or all of the traditional views on quantum theory for granted: collapse models, the Schrödinger picture, and the fundamentality of c-numbers. But if Sam is right that literally all of these aspects have to be replaced, then perhaps most of the attempts to unify general relativity with quantum mechanics had been doomed from the start.

If we follow Sam in accepting Many-Worlds quantum theory, what does the conceptual problem between physics' two pillars look like? Consider massive objects like the Sun and the planets that revolve around it. Everettian quantum theory tells us that they will all follow different trajectories (or positions at a given point in time) in different branches of the multiverse. General relativity, meanwhile, tells us that they must curve spacetime differently in each branch, since the exact shape of spacetime's curvature depends on the distribution of mass. But general relativity is a theory of c-numbers, and so, as explained in Box 1, it cannot handle something like a superposition of different spacetime curvatures. Everettian quantum theory alone tells us that masses can exist in a superposition of trajectories (or positions) across the multiverse; general relativity alone tells us that masses curve spacetime. Taken together, they imply that spacetime must be able to exist in a superposition of different curvatures, but general relativity's mathematical machinery of c-numbers cannot handle such a thing.

But Sam has already argued that we ought to drop c-numbers from physics, anyway. If c-number spacetime is the logjam preventing unification between quantum theory and general relativity, then Sam's fundamental principle of quantum theory gives us a natural path forward: express spacetime in terms of q-numbers.

We have seen that time has been incorporated into quantum theory as an emergent property, initially by Page and Wootters and then by Sam. What remains, then, is to do the same for space.

As Sam summarizes in an upcoming essay for an original Conjecture Institute compendium, "Now that time is understood as emerging naturally from quantum theory, such that it does not have to appear as a classical parameter put in by hand, it becomes difficult to treat space any differently. Likewise, it is equally difficult to maintain interpretations of quantum theory that rely on external classical structures, as all non-Everettian interpretations do. On this view, the many-worlds interpretation is not an optional philosophical gloss but a natural completion of the quantum description of reality. We are still left with the quest of unifying quantum theory and gravity, which has hitherto eluded us. But these recent advances point to a clear path forward for how to give a quantum description of not just time but potentially also space and ultimately spacetime. Hence, it might be that what is needed to understand quantum gravity is not just new ideas, but also the courage to take our existing principles seriously."

Sam's insistence on first taking our current ideas seriously before endeavoring to think up radically new ones is a kind of radical conservatism—conservative, because he argues that our best ideas already have much more fruit yet to bear if only we are willing to accept them; and radical, because so many other scientists shy away our deepest theories' implications.

In a world full of headlines touting 'the latest theory of everything', the most valuable unturned stone might be the theories we have had for a century. We just need the courage to take them seriously.

Summary

Formulating Quantum Mechanics

TRADITIONAL VIEW

Schrödinger picture and Heisenberg picture are equivalent.

SAM'S VIEW

The Heisenberg picture provides a local account of quantum systems and is therefore more fundamental than the nonlocal Schrödinger picture.

IMPLICATIONS

Many developments in quantum theory have taken the Schrödinger picture for granted and need to be recast in the Heisenberg picture (Sam solved this problem for time and for Everett's relative-state construction). Many developments in quantum theory have taken the nonlocal account provided by the Schrödinger picture for granted. This has entrenched errors in thinking, such as the idea that information jumps instantaneously from one location to another due to entanglement; these errors are fully resolved when using the Heisenberg picture, due to it being a local description.

The Collapse Postulate

TRADITIONAL VIEW

'Collapse' happens at some scale so as to yield a single, classical world.

SAM'S VIEW

The collapse postulate is unnecessary at best and problematic at worst.

IMPLICATIONS

Reality is not fundamentally classical or single-valued; observables correspond to q-numbers; Everett's relative-state construction makes more sense than collapse models; the Many-Worlds interpretation of quantum mechanics is the only interpretation that makes sense.

Q-Numbers and C-Numbers

TRADITIONAL VIEW

Q-numbers and c-numbers can both be part of our most fundamental description of reality.

SAM'S VIEW

Because of quantum theory's universality, there ought to be no c-numbers in our explanations of Nature

IMPLICATIONS

Sam's fundamental principle of quantum theory is true; c-number time must be excised from quantum theory (Sam solved this problem).

Quantum Theory and General Relativity

TRADITIONAL VIEW

Quantum theory describes the very small; general relativity describes the very large.

SAM'S VIEW

Quantum theory describes the world in terms of q-numbers; general relativity in terms of c-numbers.

IMPLICATIONS

Spacetime is a physical system, so according to the fundamental principle of quantum theory, it ought to be described by q-numbers. Such a description already exists for time, which we have a satisfactory quantum theory of, and to a lesser extent for space.

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