Talking Heads

What do baseball, penny-flipping tricksters and talking mythological serpents have in common? According to Matthew Leifer, quantum gravity. Or not.

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by KATE BECKER

FQXi Awardee: Matthew Leifer, Perimeter Institute

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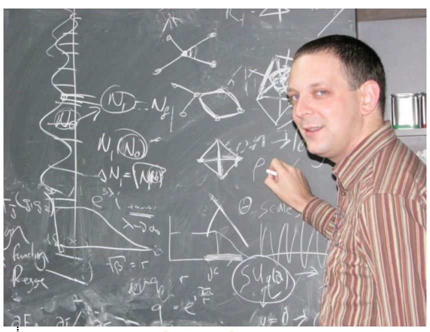
What has multiple heads, poisonous breath and the tail of a serpent?

In Greek mythology, it's a creature called a Hydra—a marsh-dwelling serpent that guards the entrance to the underworld.

But to Matthew Leifer, a theoretical physicist at Canada's Perimeter Institute, it's a creature of a very different kind: quantum theory.

Well, maybe quantum theory doesn't have poisonous breath or scales. But, Leifer says, it does have multiple heads, each one offering a different approach to the problems of quantum mechanics.



PENNY FOR YOUR THOUGHTS
Matthew Leifer

Erwin Schrödinger spoke to one head when he devised his wave function approach to quantum theory; another head guided Richard Feynman's sum-over-paths formulation. Each of these Hydra heads presents a self-contained physics, complete with its own equations, algorithms, and physical intuition about the quantum world.

While the heads agree about the observable facts of quantum physics, says Leifer, they suggest very different physical intuitions. And none of them tells the whole story of quantum theory.

"It is perfectly possible to have an intelligent dialogue with just a single head, in blissful ignorance of the existence of all the others," says Leifer.

With a US$71,680 grant from FQXi, Leifer is taking on the quantum Hydra. But he doesn't want to slay the monster; Leifer actually wants to discover another head.

Leifer's head will take its cues from the emerging technology of quantum computers—computers that use the strangest properties of quantum theory to make quick work of problems that conventional computers couldn't solve in a lifetime.

Sound exotic? It should be. If the mythological Hydra protected the entrance to the underworld, Leifer's Hydra head may be guarding the path to the "holy grail" of physics: a theory of quantum gravity.

Lucky Penny

It all starts with the most basic problem in probability: a simple coin flip.

Imagine you flip a coin 100 times. You can't predict whether the coin will land heads or tails on any particular toss—only that, if you keep flipping for a long time, the coin should come up heads just as often as tails.

Quantum theory makes similar probabilistic claims about particles: It won't tell you what any particle is doing at any given time; but it can give you the odds on any one outcome.

The mathematician John Von Neumann realized that quantum theory had a deep mathematical concordance with probability theory. Of course, the algebra of quantum theory is a little more exotic than what you learned in middle school, but make enough of the right analogies, says Leifer, and "you get precisely the structure of quantum theory."

Still, according to Leifer, von Neumann's analogy doesn't go far enough. "Quantum theory is just not abstract enough," he says. "It still contains a few too many traces of the physics to be viewed as a proper generalization of probability theory."

To illustrate, Leifer varies the classic coin flip experiment in two ways. In the first set up, imagine that you flip a single coin. You write down the outcome—heads or tails—and leave the room. Now imagine that fifty percent of the time you do this experiment, a trickster slips in and tosses the coin again. When, a few minutes later, you return to check the coin, what are the chances it will still be as you left it? Work out the odds and you'll find that three quarters of the time, you will have a matched pair of either heads or tails.

> Quantum theory is just not abstract enough.
> *- Matthew Leifer*

In the second set up, take two coins and fix them in such a way that half of the time they always show the same face, while the other half of the time the second coin is flipped randomly. Flip the coins and mail one to Mars and the other to Venus (well, it is a *thought experiment* after all). Work out the odds of getting a matched pair, and you'll find they are just the same as in the single-coin experiment: 75%.

In other words, in classical probability, it doesn't matter whether your observations are separated by time or by space: the numbers work out the same.

But in quantum theory, two different mathematical constructions are required to represent these two different scenarios. So, to truly represent quantum theory as an extension of probability theory, as von Neumann proposed, physicists will have to unite these mathematical constructions.

Leifer has taken the first steps toward doing just that. Last year, he proposed a new mathematical tool that conveys how quantum systems change over time and from place to place, all in multitasking piece. The result was published in the journal Physical Review A.

Now Leifer is working on the next steps on the road to a quantum theory – and his new Hydra head.

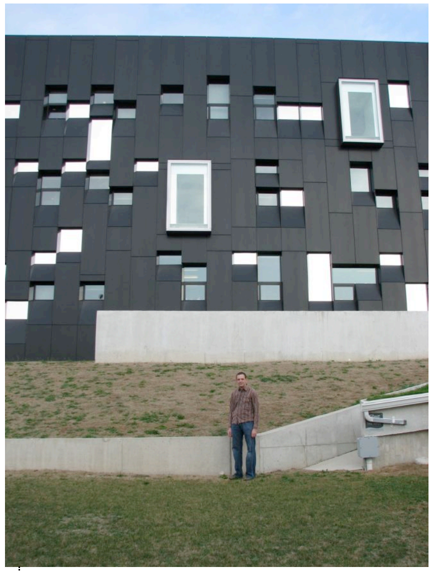
Cause and Effect

The goal of quantum gravity is to unite General Relativity, the theory by which we understand gravity and the structure of space and time, with quantum mechanics. Lucien Hardy, a researcher at the Perimeter Institute who is not part of Leifer's team, and Member of FQXi, believes that Leifer's work will bring physicists a step closer to this goal.

"Matt's work is quite remarkable," says Hardy. "He is looking at deep questions to do with causal structure within standard quantum theory."

Hardy continues, "The conceptually new feature that General Relativity brings into play is causal structure. Therefore any progress we can make in understanding the nature of causal structure in quantum theory is likely to be relevant to quantum gravity."

We usually take the "causal structure" of reality for granted: If a baseball smashes through your window, the cause (wayward baseball) and the effect (shattered glass) are clear. There is no chance that the window broke and *then* the baseball flew, or that the ball hit the window before it smacked the bat.



LOTS OF OPPORTUNITIES FOR CAUSAL STRUCTURE DEMONSTRATIONS
Matthew Leifer at Perimeter Institute

In this respect, General Relativity agrees with everyday experience: causes always precede their effects.

But when "quantum fuzziness" is added to the mix, says Leifer, causality gets more ambiguous. "Two events that are timelike separated in one component of a quantum superposition may be spacelike separated in another," says Leifer.

In other words, two events, viewed one way, may seem to occur at the same place but be separated in time, while the same two events, viewed another way, may seem to be separated in space but occur at the same time. "So there won't be a definite 'fact of the matter' about their causal relationship," says Leifer.

The lack of casual structure doesn't bode well for quantum gravity. According to Leifer, all of the leading candidates in the quantum gravity race fail to take this issue seriously. But, Leifer says, "It is worth tackling the problem head-on."

Leifer's approach to this problem is to claim ignorance, imagining that we just don't have information about the cause and effect of a particular experiment. The surprising thing, Leifer says, "is that there are whole classes of experiment for which the quantum probabilities for pairs of events are the same regardless of whether the events are timelike or spacelike related."

If this sounds strange, don't worry: We don't yet have the tools to describe these situations simply. This is what Leifer is working on: he hopes to develop the mathematical language, or Hydra's head, to render them perfectly clear.

Once that happens, Leifer hopes, it will provide true insight into the nature of reality—and finally let the Hydra speak with one voice.