A Blackboard at Brunch

In the quest for quantum gravity, one collaboration uses findings from condensed matter physics to take a fresh look at the geometry of space. Is there any?

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by KATE BECKER

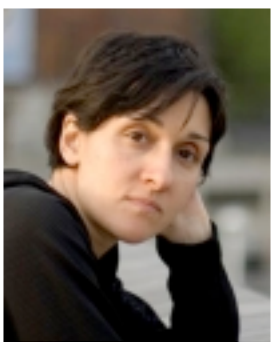
FQXi Collaboration: Markopoulou, Dreyer, Lloyd, Severini & Hamma — May 30, 2008

How many physicists does it take to change a paradigm?

Just one, say the textbooks. Think of Einstein, alone with his thoughts at the patent office; or Newton, who preferred the company of his telescope to fellow scientists.

But in the 21st century, scientific discovery is rarely a solo endeavor. Indeed, a group of theoretical physicists, while tackling one of the greatest puzzles in modern physics, is also proving that collaboration itself can be a source of creativity.

Fotini Markopoulou, Olaf Dreyer, Seth Lloyd, Simone Severini, and Alioscia



FOTINI MARKOPOULOU
Perimeter Institute

Hamma – clustered at institutions like the Massachusetts Institute of Technology and Perimeter Institute for Theoretical Physics in Waterloo, Ontario – are after what some call the holy grail of physics: quantum gravity, a "theory of everything" that would unite general relativity's mastery of all things gravitational with quantum theory's command of the subatomic realm.

To do so, these half dozen physicists are among those mining insights from the field of condensed matter physics (also called solid state physics), a broad category that encompasses everything from superconductivity to magnetism, crystal lattices to electronics. Just as condensed matter physicists have discovered surprising connections between high- and low-energy physics, these theorists believe that the physics of our present-day universe could be a special case of a deeper, more elementary system.

Bound together by this radical approach to a monumental puzzle – in a line of research still too new to have solidified into a formal field – their work occupies a corner of physics tentatively labeled "condensed matter approaches to quantum gravity." Yes, it's a bit of a mouthful, and it doesn't have the headline-ready ring of "string theory," but these scientists are hoping their approach might pay

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off where the much-more-famous front-runner has not yet succeeded.

"Researchers in condensed matter physics have discovered new orders with new properties and that has raised the question of whether things that we used to consider fundamental (say, elementary particles) are really fundamental or collective properties of something much simpler," explains Fotini Markopoulou, who is currently working at MIT while on leave from Perimeter Institute.

Olaf Dreyer, also at MIT, puts the question this way: "If solid state systems have the features of the high energy physics around us, is it then not possible that the high energy physics is the low energy behavior of some underlying solid state-like model?"

Markopoulou, Dreyer and their colleagues hope that, if they can lift the veil on that underlying model, they will find the prize so many physicists have been looking for: quantum gravity. Together, this unlikely assemblage may reshape not only our ideas about fundamental physics, but about how scientists collaborate as well.

Two (Theories) Aren't Better Than One

"How to reconcile gravity and quantum mechanics is one of the hardest outstanding problems in physics," explains

OLAF DREYER
MIT

Seth Lloyd, Director of the WM Keck Center for Extreme Quantum Information Theory (xQIT) and Professor of Mechanical Engineering at MIT. "People have been trying to quantize gravity ever since the nineteen-teens, when Einstein constructed general relativity."

General relativity is great when it comes to describing the universe on everyday scales and larger: If you want to know why apples fall from trees, why planets hew to elliptical orbits, or why a galaxy cluster rotates, gravity is your theory. Plus, general relativity – like Newton's gravity before it – is deterministic: that is, it claims that if you know everything there is to know about a system, you can predict perfectly how that system will evolve.

Quantum theory, on the other hand, embraces uncertainty. On the microscopic scale where quantum is queen, probability rules: Your yes or no question has both a yes *and* a no answer. With its maddening indecision, its free-wheeling take on reality itself, quantum mechanics clashes early and often with our intuition (largely deterministic) about how the world works.

So why not simply make do with these two well-tested if unmatched theories? First, it doesn't make sense that the universe would follow two sets of rules, one for big things and one for small things. Second, both relativity and quantum theory can be pushed to the breaking point. Third, and most troubling of all, the two theories disagree on critical questions.

SETH LLOYD
MIT

Apply the equations of gravity to the infinitely dense environment of a black hole or the Big Bang, for example, and they spit out nonsense. Let quantum mechanics play out on the scale of the everyday, and you get Schrödinger's cat, simultaneously living and dead – nonsense again.

It would seem, then, that the twin pillars of modern physics don't appear to support the same house – and that's a problem.

Out of the Loop

Enter quantum gravity: The "theory of everything" that will unite quantum theory and general relativity in a single, happy whole.

When you think of quantum gravity, you probably think of string theory, the elegant proposition that matter and the forces that govern it are like notes played out on infinitesimally small strings tucked in to "hidden dimensions" too small for the most powerful microscopes to see. A large community of researchers continues to grapple with this idea, hoping to cast it in a way that will explain the quantum behavior of space and time – and, critically, will be testable.

But others are pursuing new lines of research. There is loop quantum gravity, which seeks to recast general relativity to obey the rules of quantum mechanics. In this formulation, the fabric of space is not continuous but knitted into a discrete weave. Loop quantum gravity requires little compromise from either general relativity or quantum mechanics – each set of equations is left largely intact.

Some of the researchers now pursuing condensed matter approaches to quantum gravity started out as loop quantum gravity believers. When it was first conceived, says Dreyer, loop quantum gravity "was a very exciting field to be in. We thought we might tie up all the loose knots within the year."

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>
> *- Seth Lloyd*

But when that early promise wasn't realized, Dreyer and his colleagues were eager to try new approaches that would take loop quantum gravity in unorthodox directions. They imagined a theory that would make no initial assumptions about gravity or the geometry of space – rather, these familiar ideas would emerge from even more basic axioms of physics.

Starting From Scratch

"What is distinctive about the approaches to quantum gravity of Fotini, Seth and Olaf and their collaborators is that they are background independent, which means that there is no presumed fixed classical geometry," says Lee Smolin of Perimeter Institute. "They construct models of quantum systems that do not live in space but from whose behavior space and fields living on that space may emerge."

The advantages of starting without geometry or gravity, says Dreyer, are both practical and aesthetic. First, it saves you the trouble of "constructing a quantum-mechanical sum over geometries," a problem which Dreyer dryly notes is "extremely hard."

Second, says Dreyer, the usual approach to quantum mechanics – starting with classical mechanics, parceling it into out into quantized nuggets of energy, and hoping that the quantum world will emerge – seems backwards. "Rather, start with a quantum theory and see how the classical world arises." The best way to do this, he explains, is to start without geometry and let it emerge naturally from other principles.

The hope, says Dreyer, is that "If gravity emerges [from the model], then we can actually learn something new about gravity. We can understand gravity--why there is gravity – and not just describe it."

LEE SMOLIN
Perimeter Institute

The approach has another advantage as well: it just might be testable.

"[Our group] look[s] for quantum gravity on very large scales, not very small ones," explains Dreyer. That puts them outside of the larger community of researchers who are using particle accelerators to probe quantum gravity on the subatomic scale. But no Earthly accelerator will ever be big enough to see the "strings," perhaps leaving string theory untestable.

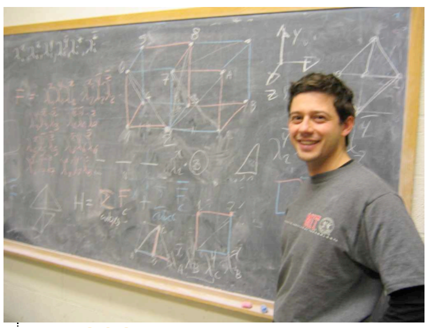
So when Dreyer says 'large scales,' he means it. To test their models, says Markopoulou, "Cosmology is the obvious place to look." That means looking at the cosmic microwave background radiation, or CMB, the electromagnetic echo of the universe as it cooled off from the Big Bang. These are all phenomenon that can be observed with existing or realistic technologies.

"Maybe that's why we like this approach," says Markopoulou. "You actually have a chance of being wrong, and you will find out soon."

Of Actors and Ice Cubes

Remove gravity and geometry from a model of the universe, and what are you left with?

The traditional understanding of matter and space is one in which "space is out there, like a theater, and things are like actors on the stage," says Alioscia Hamma, an Associate Postdoctoral Fellow at Perimeter Institute, who is currently working as a visiting scientist at MIT. "We take a completely opposite view" – one in which the actors are fundamental, and in which it is their behavior in relation to each other which ultimately defines the stage, space itself. The actors move in time with quantum mechanical evolution.



ALIOSCIA HAMMA
Perimeter Institute

"I like this approach because everything is immersed in time," says Hamma. "I like time and I do not understand why so many physicists want to say that time does not exist."

Hamma is currently working with Fotini Markopoulou on a theory punnily dubbed "quantum graphity" for its roots in graph theory. This scenario probes the possibility that geometry itself – our sense of three-dimensional location – only arises at low energies. (In this case, "low energy" describes just about everything in our modern universe.) But in a high-energy state – say, at the time of the Big Bang, or inside of a black hole – "there is no notion of a 'neighborhood,'" says Markopoulou.

"One can think of what I do as trying to make a model for the following scenario: The world started as an extremely hot, high energy soup – Planck temperature hot, compared to which the center of the hottest star is freezing cold. Maybe the notion of a space-time does not make any sense at all, quantum or not, at this early stage. It is plausible that space-time only emerged as the universe cooled down and it is not fundamental."

"It's a bit like living in a world of ice that never melts," says Markopoulou. "Would you know that water is a possibility?"

If the Big Bang had no geometrical scaffold, that would explain what cosmologists call the horizon problem: The puzzle of why the CMB is so uniform even though distant parts of the sky had no way to "communicate" their temperature to each other. "They must have been in touch," says Markopoulou, yet cosmological extrapolation from the Big Bang suggests that they never were.

Since the 1980s, theorists have used cosmic inflation to clear up the horizon problem. According to this theory, the universe got an early burst of speed – inflation – that drove its acceleration right after the Big Bang. Though inflation is a serviceable fix for many problems in cosmology, says Dreyer, "It doesn't explain the *why*."

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"A lot of ad hoc stuff goes into inflation," he explains. "It feels a bit engineered."

Dreyer, for his part, is attacking quantum gravity from a slightly different angle. His model, dubbed "Internal Relativity," does away with the traditional notion of space-time as a grid of coordinates against which objects move. Instead, Dreyer suggests, matter, space, and time all are inseparable, and we should make our measurements using only what is available to us within a system. By forsaking abstractions like clocks and rulers, say, Dreyer conjectures that the fundamental rules of relativity may emerge naturally from these simple elements.

Joining Forces

The emerging field of condensed matter approaches to quantum gravity is brimming with ideas, and so it remains to be seen which ones will stick around – and which won't. It helps to have a large community of similarly interested researchers to separate "keepers" from ideas that can be tossed in the wastebasket.

"It is normal to have large collaborations in physics today," says Simone Severini, a researcher at the Institute for Quantum Computing and the Department of Combinatorics and Optimization at the University of Waterloo. The biggest teams of all – comprising hundreds of researchers – are found in experimental physics, but "for basically intellectual work, it is a little more difficult to share tasks with others. However, the trend is going towards larger collaborations also in theoretical physics and mathematics."

"It's very complicated to make sure you're not biting your own tail" when working in isolation, admits Hamma. In a large collaboration, you cannot get too attached to any single idea or approach,

SIMONE SEVERINI
University of Waterloo

but thanks to the constant back-and-forth of questions and criticism from colleagues, says Hamma, every day is a "continuous change of heart."

Of his own collaborators, Severini says: "We work together in all possible ways. In person, on the phone, on Skype, over email, at conferences. When you collaborate with someone, this someone is already or will become your friend. Where do you see your friends? Everywhere you can."

Says Hamma, "We can spend hours talking and at some point suddenly it is very late, and we are exhausted, and we say, oh maybe we could get some food."

"It is funny and often useful to discover that there is someone who does exactly the same but it calls it differently," says Severini. "If you manage to 'communicate' beyond the language barrier, then it may turn out that you can help each other."

Dreyer and Markopoulou, who were married in 2006, have a unique model of collaboration. Their workdays typically begin at home, with a simple set of tools: Coffee, tea, and a homemade blackboard installed in every home they've shared. In one apartment, the board went up in the study; in another, it covered a "horrible, evil" mural of trees painted on the living room wall. Their trip to Home Depot to buy chalkboard supplies has become a ritual marking each change of address.

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Dreyer and Markopoulou start talking physics in the morning: "You have your first coffee or tea and then your brain wakes up," says Dreyer. But if you're imagining the pair dazzling each other over brunch just so with their overnight epiphanies, think again – more often, Markopoulou and Dreyer say, they seek each other's guidance as they struggle to untangle something they're confused or unclear on. "We are better at realizing something *doesn't* make sense" than that it does, says Markopoulou.

With so many competing ideas, how do the researchers keep their competitive instincts from sabotoging their collaborations? Frankly, says Hamma, the fledgling ideas are so young that it is still "difficult to know what the theory is saying." So "I don't know whether our approaches are different or not," says Hamma.

Markopoulou echoes the sentiment: "It's possible that [Dreyer's] model and my model are incompatible. Or, maybe they are two sides of the same story."

To Lloyd, the point isn't who is right and who is wrong: It is about being part of a group that welcomes new ideas, however unconventional. "I have very much enjoyed collaborating with Fotini, Olaf, Alioscia," and the rest of the team, he says. "Their minds are open, and open minds are hard to find."

A BLACKBOARD AT BRUNCH
Markopoulou and Dreyer use theirs differently