# FULL CIRCLE PHYSICS

*From left: IQIM members John Preskill, Shaun Maguire, Chandni U., and Oskar Painter.*

*Caltech's Institute for Quantum Information and Matter (IQIM) began in 2010 as the Center for Exotic Quantum Systems, funded by the Gordon and Betty Moore Foundation as part of what it called its Caltech Commitment. By 2011, it had become so successful that it did exactly what the Moore Foundation had hoped it would do—it outgrew its original concept, garnering wide interest and additional funding from the National Science Foundation to become a Physics Frontiers Center that studies "physical systems in which the weirdness of the quantum world becomes manifest on macroscopic scales." Its research programs range from quantum information science to quantum condensed-matter physics, quantum optics, and the quantum mechanics of mechanical systems. By bringing together theorists and experimentalists under the same roof, IQIM has created a continuous, collaborative feedback loop to take quantum science to the next level.*

*With the help of interviews conducted by IQIM communications coordinator Crystal Dilworth (PhD '14) and filmmaker Iram Parveen Bilal (BS '04),* E&S *talked with several IQIM scientists about the frontiers of quantum science, the role IQIM plays in exploring that frontier, and the question oft thought but rarely spoken: Why should we care? Here—in a "conversation" assembled from separate interviews—are some of their insights into what makes the world of the tiny such a big deal.*

## WHY IS QUANTUM SCIENCE SO EXCITING?

**John Preskill, the Richard P. Feynman Professor of Theoretical Physics:** Everybody wants to understand the world, right? And there are all kinds of things that I don't understand. But physics is a way of making sense of the world. And it works. It's an amazing thing. It keeps happening again and again—that we can formulate these simple laws; we can do calculations on a pad of paper with a pen, which describe very deep and subtle things about nature; and we can test those ideas; and they *work*. It's so astonishing.

This is an amazing time in quantum science. A new frontier of physics is opening up, which is very fundamental and exciting. You can call it the entanglement frontier, or the complexity frontier. New phenomena occur when you put many particles together, behavior we can't simulate using our ordinary digital computers. In some cases we can predict accurately what will happen, but in many cases we don't know what to expect. Eventually this new frontier will have a big impact on technology—I don't think there's any doubt about that. But that's not really what excites us now. What excites us are the opportunities for fundamental discovery.

Imagine that for thousands of years we've been trying to push science and technology forward, but we didn't know anything about decimal arithmetic; we were stuck using Roman numerals. There are so many things we would like to be able to do, problems to solve, mathematical challenges, but we just don't have the right tools, the right computational concepts to go forward.

Quantum computing is like that. All these thousands of years human civilization has been missing this special sauce that is going to take information to a new level. And now we can glimpse what it is. We don't yet know for sure where it's leading. But it's going to be something big.

**Chandni U., IQIM postdoctoral scholar in physics:** Quantum science is fun and tough because it is often hard to explain or comprehend. It breaks our conventional understanding of the way the world works. I study the tunneling of electrons in atomically thin systems, and when I need to explain it to friends or family, I still use analogies like a lion penetrating through an infinitely tall wall, which is a bizarre concept in the world we are used to.

there are a wide range of interesting fundamental and applied problems to be studied in quantum physics. Being an engineer at heart, I am drawn to the opportunities to develop new, more powerful technologies utilizing the quantum features of nature.

WE'RE AN ENTANGLED COMMUNITY OF SCIENTISTS WITH DIFFERENT BACKGROUNDS, BUT WITH ENOUGH COMMON GROUND TO ENGAGE WITH ONE ANOTHER FRUITFULLY.

This journey toward understanding something that we see around us is very stimulating. Even if it is something that the whole world already knows, when you learn it in a textbook, solve an equation, or measure something in the lab, that feeling is very exciting and encouraging. You don't do science hoping to make discoveries on a daily basis. The quest and little findings push you every single day. But on rare days you do observe some new phenomenon, something that only you have noticed. Even if it is a small discovery, it is thrilling because you know you have just nudged the boundaries of knowledge a bit.

**Shaun Maguire, graduate student in mathematics:** We've kind of made it past an inflection point in terms of actually being able to do experiments that probe the foundations of quantum mechanics. The sheer diversity of experiments happening right now is giving theorists a lot of ideas about what research directions to pursue next.

**Oskar Painter, the John G Braun Professor of Applied Physics:** To me, quantum physics is one of the more interesting areas of science in that we have solid mathematical models for predicting quantum behavior, but we are still rather immature in our ability to utilize these models in practice, either in calculating the properties of complex quantum systems or in building technologies that take advantage of uniquely quantum features. As a result, we don't fully appreciate yet all the subtle aspects of quantum systems, and

## WHAT IS IQIM ALL ABOUT, AND WHY IS IT SPECIAL?

**Preskill:** IQIM is, first of all, an assemblage of different research groups—it involves 20 Caltech faculty members all doing fantastic science. IQIM brings us together, sparking progress that just wouldn't happen if these groups were acting individually rather than as part of a larger community. If you bring theorists in close contact with experimentalists and you start talking about the problems of common interest and really seriously engage with one another, it gives you new ideas. You think about things in a different way. You develop an understanding of what the theorists can and can't do, and what the experimentalists can and can't do. That's really why it's important that we are a unified institute rather than just a bunch of groups.

**Painter:** Experimentally, within IQIM, we are exploring a diverse set of research topics. These include fundamental studies of materials with topological order arising from long-range quantum entanglement between particles, as well as of new synthetic quantum materials that can be built up from individual gas-phase atoms interacting with photons in nano-structured materials. Researchers are also developing new techniques and technologies for performing precision measurement of mechanical objects that meet or exceed standard quantum limits set by the intrinsic uncertainty or "fuzziness" of quantum-mechanical systems. Such methods, for instance, are crucial to instruments such as the Laser Interferometer Gravitational-Wave Observatory that are searching for the hints of gravitational waves in the tiny deflections of mechanically compliant mirrors.

The IQIM is special in that we experimentalists maintain close contact with our theoretical colleagues, learning about ideas that may be 10, 20, or even 50 years ahead of their time. This gives us a great advantage in picking interesting problems to work on. For instance, a new research effort in my own group seeks to exploit the properties of superconducting electrical circuits to build quantum circuits of artificial "atoms" that can perform quantum computations, a computing method thought to be much more powerful than can be realized with classical machines. The hardware we are developing has been around for a little over a decade, but new, important ideas for how to effectively use the hardware are being developed today by IQIM theorists such as John Preskill, Alexei Kitaev, and their students and postdocs.

**Maguire:** The IQIM is this ecosystem of people thinking about problems that exist on a one-year timescale all the way to the 100-year-and-more timescale. I am all the way on the furthest extreme. But you have people who are thinking about the next generation of how you can transmit quantum information about the world—you can think of this as the next version of the Internet, the quantum Internet. We have people making breakthroughs in materials science and on the verge of fundamental physics, things like exploring topological insulators, people working on graphene, which has a lot of promising applications in a huge number of fields.

We're about four years into IQIM, and it just feels like there are enough ideas floating around and enough people doing really interesting things that some of those things are going to stick and become huge, substantial breakthroughs. It's an exciting thing to be a part of right now.

**Chandni:** IQIM is a conglomeration of people with varied interests who are extremely passionate about their science. We think of different aspects of quantum science, computing, and matter in our confined spaces, but when together as an entity we focus on the bigger picture of creating and manipulating the next generation of quantum computers and related applications. Personally, IQIM has taught me to think big. We often narrow down our thoughts and scientific perspectives because we are so focused on tackling the day-to-day issues with our research. However, IQIM brings together those many aspects under a broad vision and gives them depth and purpose.

**Preskill:** Big scientific advances often occur when different ideas collide and get synthesized. We're seeing that in a number of different ways in what we're doing at IQIM today.

Quantum entanglement is a unifying idea that encompasses a lot of the science that we work on. When a quantum system is highly entangled, that means the information carried by the system is spread out very nonlocally. You can't read that information by looking at the parts of the system one at a time, because the information is really stored in how the parts are correlated with one another. By thinking hard about entanglement, applying ideas that were originally developed for understanding quantum computers, we've found new ways to classify the different possible types of quantum materials. Insights borrowed from quantum computing are even giving us new ways to approach deep issues in quantum gravity, like the quantum properties of black holes and the fundamental structure of space and time. What's really exciting to me is that we might be able to test some of these ideas experimentally.

It takes a community to make progress because these problems are hard, they're very interdisciplinary. Computer scientists have part of the answer, experimental physicists know a lot of the tools that are relevant, theoretical physicists, people from information theory—all of them have pieces of the puzzle. And you have to get them together and create an intellectual climate where ideas are flying around and everyone benefits from everyone else's knowledge and background—that's what we're doing at IQIM. We're an entangled community of scientists with different backgrounds, but with enough common ground to engage with one another fruitfully. It's really exciting.

Public outreach is also a huge part of what we do at IQIM. We produce videos with Jorge Cham, the creator of PhD Comics, which explain quantum concepts in an engaging way. In collaboration with Google and MinecraftEdu we created qCraft, a game that teaches kids about how to manipulate quantum systems. Our blog Quantum Frontiers provides a personal perspective on quantum science. See our website for much more.

## IT'S EXCITING TO YOU, BUT WHY SHOULD THE REST OF US CARE ABOUT QUANTUM SCIENCE?

**Painter:** When we start talking about quantum mechanics nowadays to a layperson, I think it's a lot easier because the experiments we're doing are more tangible. We've built up these quantum systems to a larger scale, to scales in which we start to have an everyday appreciation for the objects involved. It's not just at the atomic scale. For example, we are now able to measure the quantum properties of mechanical objects, ones which can be seen with the naked eye, or of electrical circuits similar to those found in your cell phone. So it's become a little bit easier to talk about quantum mechanics to the average person on the street.

It's also very likely that quantum mechanical concepts will be more relevant to such a person. In the decades to come, as we become more proficient in making devices that compute things or communicate information utilizing the principles of quantum mechanics, there will be a need to understand concepts such as superposition and entanglement by those who use these technologies.

**Chandni:** At least in some form, you will probably have a quantum computer in a few years' time. As for materials, topological insulators, which is one of the things we talk about, I think it will have a lot of other applications like in power devices, where the goal is to have low power consumption. Graphene people say *that* material can revolutionize a lot of fields, including flexible electronics and so on.

We need to remember that the public was not that interested in normal computers not that long ago. Right now, quantum science is just cool science stuff. But if you want to have a good future where you have even smarter smartphones, then quantum computing is important.

**Preskill:** How is this going to affect people in their everyday lives? I don't know. But I think it will, and in profound ways. And the reason I think that . . . well, of course we know how important information and information processing are now in our daily lives. And what we're talking about with quantum computing is a whole different way of thinking about and manipulating information. It's not just a much, much faster computer; it's really a different paradigm for what information is and how we can make use of it.

It's kind of a mystery why physics is so successful, why we, human beings who have many limitations, who evolved for a much different purpose than to probe the deepest secrets of nature, can be so successful at it. It's hard. There are many puzzles. Nature is subtle and it's always a struggle to answer the big questions, but we make progress and it's just so satisfying when we do. e&s