THE REALITY TESTS

A team of physicists in Vienna has devised experiments that may answer one of the enduring riddles of science: **DO WE CREATE THE WORLD JUST BY LOOKING AT IT?**

BY JOSHUA ROEBKE PHOTOGRAPHY BY MARK MAHANEY

ANTON ZEILINGER (opposite) heads up the IQOQI lab in Vienna.

TO ENTER THE SOMEWHAT formidable Neo-Renaissance building at Boltzmanngasse 3 in Vienna, you must pass through a small door sawed from the original cathedral-like entrance. When I first visited this past March, it was chilly and overcast in the late afternoon. Atop several tall stories of scaffolding there were two men who would hardly have been visible from the street were it not for their sunrise-orange jumpsuits. As I was about to pass through the nested entrance, I heard a sudden rush of wind and felt a mist of winter drizzle. I glanced up. The veiled workers were power-washing away the building's façade, down to the century-old brick underneath.

In 1908 Karl Kupelwieser, Ludwig Wittgenstein's uncle, donated the money to construct this building and turn Austria-Hungary into the principal destination for the study of radium. Above the doorway the edifice still bears the name of this founding purpose. But since 2005 this has been home of the Institut für Quantenoptik und Quanteninformation (IQOQI, pronounced "ee-ko-kee"), a center devoted to the foundations of quantum mechanics. The IQOQI, which includes a sister facility to the southwest in the valley town of Innsbruck, was initially realized in 2003 at the behest of the Austrian Academy of Sciences. However, the institute's conception several years earlier was predominantly due to one man: Anton Zeilinger.

This past January, Zeilinger became the first ever recipient of the Isaac Newton Medal for his pioneering contributions to physics as the head of one of the most successful quantum optics groups in the world. Over the past two decades, he and his colleagues have done as much as anyone else to test quantum mechanics. And since its inception more than 80 years ago, quantum mechanics has possibly weathered more scrutiny than any theory ever devised. Quantum mechanics appears correct, and now Zeilinger and his group have started experimenting with what the theory means.

Some physicists still find quantum mechanics unpalatable, if not unbelievable, because of what it implies about the world beyond our senses. The theory's mathematics is simple enough to be taught to undergraduates, but the physical implications of that mathematics give rise to deep philosophical questions that remain unresolved. Quantum mechanics fundamentally concerns the way in which we observers connect to the universe we observe. The theory implies that when we measure particles and atoms, at least one of two long-held physical principles is untenable: Distant events do not affect one other, and properties we wish to observe exist before our measurements. One of these, locality or realism, must be fundamentally incorrect.

For more than 70 years, innumerable physicists have tried to disentangle the meaning of quantum mechanics through debate. Now Zeilinger and his collaborators have performed a series of experiments that, while neatly agreeing with the theory's predictions, are reinvigorating these historical dialogues. In Vienna experiments are testing whether quantum mechanics permits a fundamental physical reality. A new way of understanding an already powerful theory is beginning to take shape, one that could change the way we understand the world around us. Do we create what we observe through the act of our observations?

MOST OF US WOULD AGREE that there exists a world outside our minds. At the classical level of our perceptions, this belief is almost certainly correct. If your couch is blue, you will observe it as such whether drunk, in high spirits, or depressed; the color is surely independent of the majority of your mental states. If you discovered your couch were suddenly red, you could be sure there was a cause. The classical world is real, and not only in your head. Solipsism hasn't really been a viable philosophical doctrine for decades, if not centuries.

But none of us perceives the world as it exists *fundamentally*. We do not observe the tiniest bits of matter, nor the forces that move them, individually through our senses. We evolved to experience the world in bulk, our faculties registering the net effect of trillions upon trillions of particles or atoms moving in concert. We are crude measurers. So divorced are we from the activity beneath our experience that physicists became relatively assured of the existence of atoms only about a century ago.

Physicists attribute a fundamental reality to what they do not directly perceive. Particles and atoms have observable effects that are well described by theories like quantum mechanics. Single atoms have been "seen" in measurements and presumably exist whether or not we observe them individually. The properties that define particles—mass, spin, etc.—are also thought to exist before we measure them. In physics this is how reality is defined; particles and atoms have measurable properties that exist prior to measurement. This is nothing stranger than your blue couch.

OLD SCHOOL
The nested entrance to the IQOQI building. A century-old blackboard in Anton Zeilinger's office once owned by another famous Viennese physicist, Ludwig Boltzmann.

SOME PHYSICISTS STILL FIND QUANTUM MECHANICS UNPALATABLE, IF NOT UNBELIEVABLE, BECAUSE OF WHAT IT IMPLIES ABOUT THE WORLD.

As a physical example, light consists of particles known as photons that each have a property called polarization. Measuring polarization is usually something like telling time; the property can be thought of like the direction of a second hand on a clock. For unpolarized light, the second hand can face any direction as with a normal clock; for polarized light the hand will face in only one or a few directions, as if the clock were broken. That photons can be polarized is, in fact, what allows some sunglasses to eliminate glare—the glasses block certain polarizations and let others through. In Vienna the polarization of light is also being used to test reality.

For a few months in 2006, Simon Gröblacher, who had started his PhD not long before, spent his Saturdays testing realism. Time in the labs at the IQOQI is precious, and during the week other experiments with priority were already underway. Zeilinger and the rest of their collaborators weren't too worried that this kind of experiment would get scooped. They were content to let Gröblacher test reality in the lab's spare time.

It was after 2 pm when I first met Gröblacher, and he had just woken up; they are installing an elevator in his lab and so he works nights. He had told me to come to the top floor of the IQOQI building to find him. I made my way up the broad granite steps, and on the final landing I heard shouts from a half-open door. There was a raucous game of foosball in the lounge. When Gröblacher saw me, someone else grabbed the handles.

The lab where Gröblacher performed the first experiment on realism is on the second floor of the Universität Wien physics department, which connects to the IQOQI through a third-floor bridge. The original experiment has given way to another, but, Gröblacher tells me, the setup looks roughly the same.

In the middle of the cramped space is a floating metal surface, about the size of a banquet table, latticed with drill holes. A forest of black optical equipment, like monocles atop tiny poles, seems to grow out of the table. Beam splitters resemble exact, glass die. In the center is an encased crystal that is not visible, and on the ends sit idle lasers.

Gröblacher walked me through the tabletop obstacle course: The laser light passes through a series of polarizers and filters, hits the crystal, and splits into two beams of single-file photons. Detectors in both beams measure the polarization of each photon, which are related to one another. The data is tested against two theories: one that preserved realism but allowed strange effects from anywhere out there in the universe, and quantum mechanics.

The whole experiment would fit snugly in a child's bedroom, and as I looked at the table, I refrained from asking my first instinctual questions. "This is it? This is where you tested realism?" I already knew how unfair these questions were. It had taken a few months of tests, and almost two years for Zeilinger's group to understand how this experiment tests realism. Before that, it had been more than 80 years since physicists began to argue about what quantum mechanics had to do with reality at all.

IN THE SUMMER OF 1925, Werner Heisenberg was stricken with hay fever and having trouble with math. He asked his advisor for two weeks off and left for a barren island in the North Sea. He spent his mornings swimming and hiking, but every evening Heisenberg tried to describe atoms in a theory that included only what could be measured. One night, feverish with insight, he calculated until dawn. After Heisenberg put down his pencil as the sun began to rise, he walked to the tip of the island, confident he had discovered quantum mechanics.

By this time a quarter century had passed since Max Planck first described energy as whole-number multiples of a basic unit, which he called the quantum. When two of the quantum's other leading progenitors, Niels Bohr and Albert Einstein, heard about Heisenberg's completion of the work they began, their reactions were almost immediate; Bohr was impressed, Einstein was not. Heisenberg's theory emphasized the discrete, particle-like nature of matter, and Einstein, who tended to think in images, could not picture it in his head.

In Switzerland, Erwin Schrödinger had also been "repelled" by Heisenberg's theory. In the fall of 1925, Schrödinger was 38 years old and rife with self-doubt, but when Einstein sent him an article describing a possible duality between particles and waves, Schrödinger had an idea. Over a period of six months, he published five papers outlining a wave theory of the atom. Though it proved difficult to physically interpret what his wave was, the theory felt familiar to Schrödinger. Heisenberg, who had moved to Copenhagen to become Bohr's assistant, thought the theory "disgusting."

Schrödinger and Heisenberg independently uncovered dual descriptions of particles and atoms. Later, the theories proved equivalent. Then in 1926 Heisenberg's previous advisor, Max Born, discovered why no one had found a physical interpretation for Schrödinger's wave function. They are not physical waves at all; rather the wave function includes all the possible states of a system. Before a measurement those states exist in *superposition*, wherein every possible outcome is described at the same time. Superposition is one of the defining qualities of quantum mechanics and implies that individual events cannot be predicted; only the probability of an experimental outcome can be derived.

The following year, in 1927, Heisenberg discovered the uncertainty principle, which placed a fundamental limit on certain measurements. Pairs of specific quantities are incompatible observables; momentum and position, energy and time, and other measurable pairs cannot be known together with absolute accuracy. Measuring one restricts knowledge of the other. With this quantum mechanics had become a full theory. But what physicists ended up with was a world divided. There was an inherent distinction between atoms unseen and their collective motion we witness with our eyes—the quantum versus the classical. While the distinction appeared physical, many, like Bohr, thought it philosophical; the theory lacked a proper interpretation.

According to Bohr every measuring device affects what it is used to observe. The quantum world is discrete and so there can never be absolute precision during a measurement. To know about quantum mechanics, we rely on classical devices. To Bohr this implied that the hierarchy between observer and observed had no meaning; they were nonseparable. Concepts once thought to be mutually exclusive, such as waves and particles, were also complements. The difference was only language.

By contrast Einstein was a realist who believed in a world independent of the way it is measured. During a set of conferences at the Hotel Metropole in Brussels, he and Bohr argued famously over the validity of quantum mechanics and Einstein presented a number of thought experiments intended to show the theory incorrect. But when Bohr used Einstein's own theory of relativity to evade one of these thought experiments, Einstein was so stung he never tried to disprove quantum mechanics again, though he continued to criticize it.

In 1935, from an idyllic corner of New Jersey, Einstein and two young collaborators began a different assault on quantum mechanics. Einstein, Podolsky, and Rosen (EPR) did not question the theory's correctness, but rather its completeness. More than the notion that god might play dice, what most bothered Einstein were quantum mechanics' implications for reality. As Einstein prosaically inquired once of a walking companion, "Do you really believe that the moon exists only when you look at it?"

The EPR paper begins by asserting that there's a real world outside theories. "Any serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates." If quantum mechanics is complete, then "every element of physical reality must have a counterpart in the physical theory." EPR argued that objects must have preexisting values for measurable quantities and that this implied that certain elements of reality could not be determined by quantum mechanics.

Einstein and his colleagues imagined two electrons that collide and fly apart. After the collision the electrons exist in a state of superposition of the possible values for their momenta. Mathematically and physically, it makes no sense to say that either electron has a definite momentum independent of the other before measurement; they are "entangled." But when one electron's momentum is measured, the value of the other's

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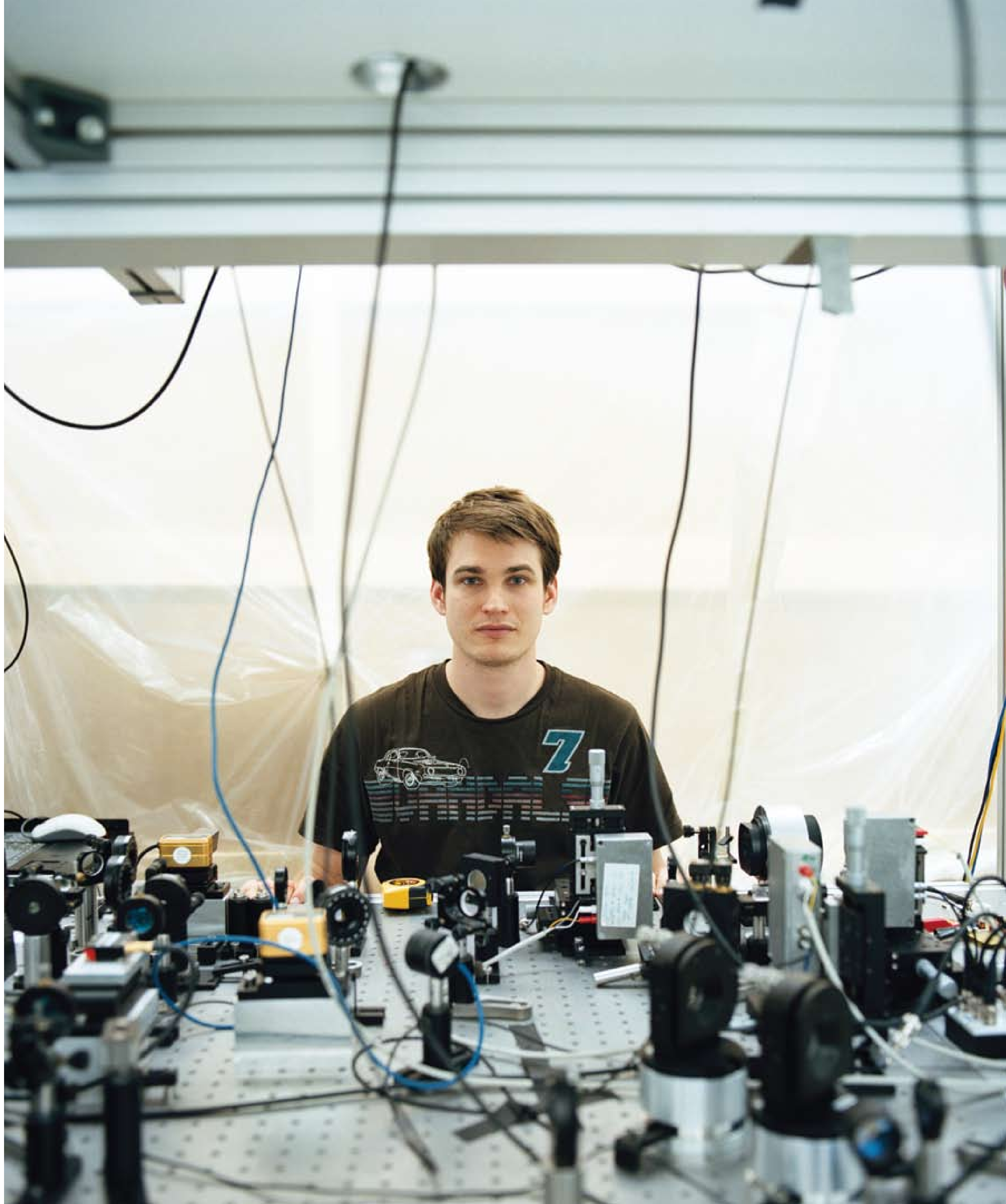
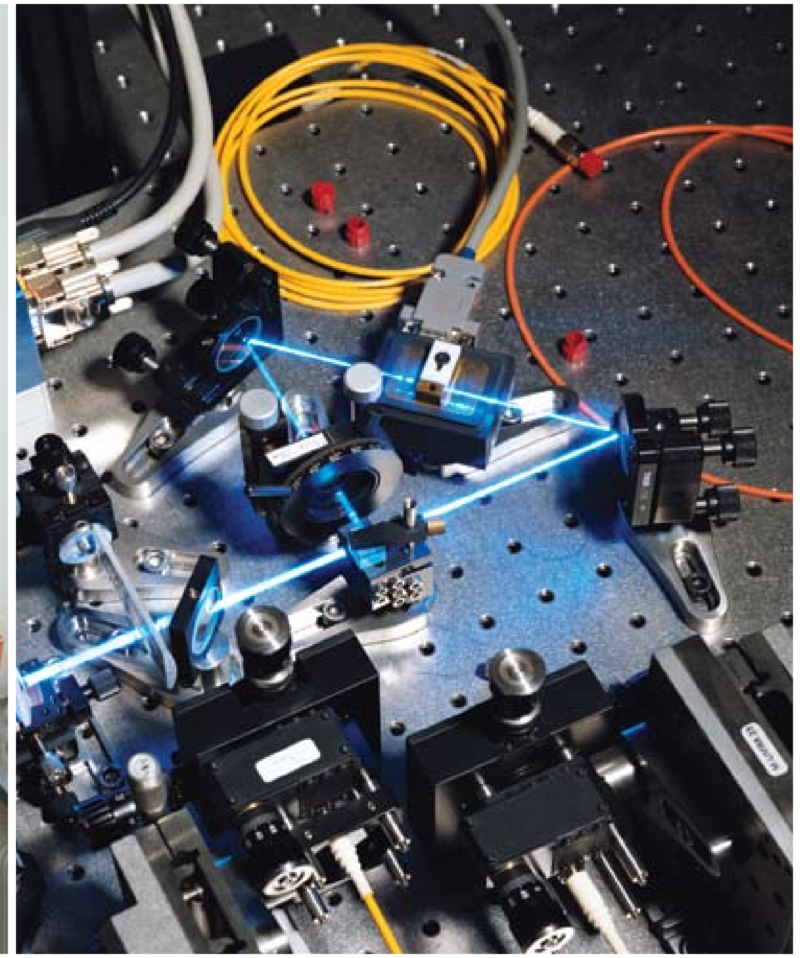
THE YOUNG TURK
PhD student Simon Gröblacher sits behind the floating table where he spends evenings doing Schrödinger's cat-style experiments.





is instantly known and the superpositions collapse. Once the momentum is known for a particle, we cannot measure its position. This element of reality is denied us by the uncertainty principle. Even stranger is that this occurs even when the electrons fly vast distances apart before measurement. Quantum mechanics still describes the electrons as a single system across space. Einstein could never stomach that an experiment at one electron would instantaneously affect the other.

In Copenhagen Bohr began an immediate response. It didn't matter if particles might affect one another over vast distances, or that particles had no observable properties before they are observed. As Bohr later said, "There is no quantum world. There is only an abstract quantum physical description."

Physicists' discourse on reality began just as the world slid inexorably toward war. During WWII physicists once interested in philosophy worried about other issues. David Bohm, however, did worry. After the war Bohm was a professor at Princeton, where he wrote a famous textbook on quantum mechanics. Einstein thought it was the best presentation of quantum mechanics he had read, and when Bohm began to challenge the theory, Einstein said, "If anyone can do it, then it will be Bohm."

In 1952, during the Red Scare, Bohm moved to Brazil. There he discovered a theory in which a particle's position was determined by a "hidden variable" even when its momentum was absolutely known. To Bohm reality was important, and so to preserve it, he was willing to abandon locality and accept that entangled particles influenced one another over vast distances. However, Bohm's hidden variables theory made the same predictions as quantum mechanics, which already worked.

In America Bohm's theory was ignored. But when the Irishman John Bell read Bohm's idea, he said, "I saw the impossible done." Bell thought hidden variables might show quantum mechanics incomplete. Starting from Bohm's work, Bell derived another kind of hidden variables theory that could make predictions different from those of quantum mechanics. The theories could be tested against one another in an EPR-type experiment. But Bell made two assumptions that quantum mechanics does not; the world is local (no distant influences) and real (preexisting properties). If quantum mechanics were correct, one or both of these assumptions were false, though Bell's theorem could not determine which.

Bell's work on local hidden variables theory stirred little interest until the 1970s, when groups lead by John Clauser, Abner Shimony, and others devised experimental schemes in which the idea could be tested with light's polarizations instead of electrons' momentum. Then in 1982 a young Frenchman named Alain Aspect performed a rigorous test of Bell's theory on which most physicists finally agreed. Quantum mechanics was correct, and either locality or realism was fundamentally wrong.

During the 1980s and 1990s, the foundations of quantum mechanics slowly returned to vogue. The theory had been shown, with high certainty, to be true, though loopholes in experiments still left some small hope for disbelievers. However, even to believers, nagging questions remained: Was the problem with quantum mechanics locality, realism, or both? Could the two be tested?

IN MAY OF 2004 Markus Aspelmeyer met Anthony Leggett during a conference at the Outing Lodge in Minnesota. Leggett, who had won the Nobel Prize the year before, approached Aspelmeyer, who had recently become a research assistant to Zeilinger, about testing an idea he first had almost 30 years before.

In 1976 Leggett left Sussex on teaching exchange to the University of Science and Technology in Kumasi, the second largest city in Ghana. For the first time in many years, he had free time to really think, but the university's library was woefully out of date. Leggett decided to work on an idea that didn't require literature because few had thought about it since David Bohm: nonlocal hidden variables theories. He found a result, filed the paper in a drawer, and didn't think about it again until the early 2000s.

Leggett doesn't believe quantum mechanics is correct, and there are few places for a person of such disbelief to now turn. But Leggett decided to find out what believing in quantum mechanics might require. He worked out what would happen if one took the idea of nonlocality in quantum mechanics seriously, by allowing for just about any possible outside influences on a detector set to register polarizations of light. Any unknown event might change what is measured. The only assumption Leggett made was that a natural form of realism hold true; photons should have measurable polarizations that exist before they are measured. With this he laboriously derived a new set of hidden variables theorems and inequalities as Bell once had. But whereas Bell's work could not distinguish between realism and locality, Leggett's did. The two could be tested.

When Aspelmeyer returned to Vienna, he grabbed the nearest theorist he could find, Tomasz Paterek, whom everyone calls "Tomek." Tomek was at the IQOQI on fellowship from his native Poland and together, they enlisted Simon Gröblacher, Aspelmeyer's student. With Leggett's assistance, the three spent six months painfully checking his calculations. They even found a small error. Then they set about recasting the idea, with a few of the other resident theorists, into a form they could test. When they were done, they went to visit Anton Zeilinger. The experiment wouldn't be too difficult, but understanding it would. It took them months to reach their tentative conclusion: If quantum mechanics described the data, then the lights' polarizations didn't exist before being measured. Realism in quantum mechanics would be untenable.

DOUBLE CHECKING
Alessandro Fedrizzi, another PhD student at the IQOQI, and the experimental setup he constructed for a second rigorous test of realism in mid-2007.

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ON MY FINAL MORNING IN VIENNA, snow was tumbling like dryer sheets as I stared out the window of the IQOQI waiting to speak again with Zeilinger. Suddenly, there was a great flash of lightning and a long roll of thunder as snow continued to fall. I turned around to no one and Zeilinger's assistant appeared. He now had time to talk.

Though less robust and more intimidating, Zeilinger bears a slight resemblance to the American Kris Kringle. Born in 1945, he is tall and stout with a beard and white mane of hair. He wears tailored jackets, though insists he is a hands-on kind of guy.

As a student in Vienna in the 1960s, Zeilinger never attended a single course in quantum mechanics, which may help to explain the way he has investigated it since—with the zeal of a late convert. In the past decade or so, Zeilinger and his many collaborators were the first to teleport light, use quantum cryptography for a bank transaction (with optical fibers in the sewers of Vienna), realize a one-way quantum computer, and achieve entanglement over large distances through the air, first across the Danube River and then between two of the Canary Islands. Zeilinger's work had also previously shown the greatest distinction between quantum mechanics and local realism.

Zeilinger's office is large and sparsely decorated. A few books lean on a lengthy, glass-fronted bookshelf. As he spoke, Zeilinger reclined in a black chair, and I leaned forward on a red couch. "Quantum mechanics is very fundamental, probably even more fundamental than we appreciate," he said, "But to give up on realism altogether is certainly wrong. Going back to Einstein, to give up realism about the moon, that's ridiculous. But on the quantum level we do have to give up realism."

With eerie precision, the results of Gröblacher's weekend experiments had followed the curve predicted by quantum mechanics. The data defied the predictions of Leggett's model by three orders of magnitude. Though they could never observe it, the polarizations truly did not exist before being measured. For so fundamental a result, Zeilinger and his group needed to test quantum mechanics again. In a room atop the IQOQI building, another PhD student, Alessandro Fedrizzi, recreated the experiment using a laser found in a Blu-ray disk player.

Leggett's theory was more powerful than Bell's because

THE GROUP
Above, Časlav Brukner sits across from Markus Aspelmeyer. Below, Brucker stands between two other theorists: Johannes Kofler (left) and Tomasz Paterek (right).

it required that light's polarization be measured not just like the second hand on a clock face, but over an entire sphere. In essence, there were an infinite number of clock faces on which the second hand could point. For the experimenters this meant that they had to account for an infinite number of possible measurement settings. So Zeilinger's group rederived Leggett's theory for a finite number of measurements. There were certain directions the polarization would more likely face in quantum mechanics. This test was more stringent. In mid-2007 Fedrizzi found that the new realism model was violated by 80 orders of magnitude; the group was even more assured that quantum mechanics was correct.

Leggett agrees with Zeilinger that realism is wrong in quantum mechanics, but when I asked him whether he now believes in the theory, he answered only "no" before demurring, "I'm in a small minority with that point of view and I wouldn't stake my life on it." For Leggett there are still enough loopholes to disbelieve. I asked him what could finally change his mind about quantum mechanics. Without hesitation, he said sending humans into space as detectors to test the theory. In space there is enough distance to exclude communication between the detectors (humans), and the lack of other particles should allow most entangled photons to reach the detectors unimpeded. Plus, each person can decide independently which photon polarizations to measure. If Leggett's model were contradicted in space, he might believe. When I mentioned this to Prof. Zeilinger he said, "That will happen someday. There is no doubt in my mind. It is just a question of technology." Alessandro Fedrizzi had already shown me a prototype of a realism experiment he is hoping to send up in a satellite. It's a heavy, metallic slab the size of a dinner plate.

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ON MARKUS ASPELMEYER'S DESK there are three tall empty boxes of Veuve Clicquot. Experimentalists at the IQOQI receive champagne for exceptional results, and on one of the boxes are written congratulations for Markus's initiation of the realism test. Časlav Brukner, who helped with the theory, keeps a squat box of Chinese plum wine on his desk facing Markus's. When I asked about the wine, thinking it the theorists' complementary tradition, he laughed and said he just needed a counterbalance. Brukner has an easy manner and has been with Zeilinger's group almost continuously since arriving in Austria in 1991 after leaving then Yugoslavia.

Last year Brukner and his student Johannes Kofler decided to figure out why we do not perceive the quantum phenomena around us. If quantum mechanics holds universally for atoms, why do we not see directly its effects in bulk?

Most physicists believe that quantum effects get washed out when there are a large number of particles around. The particles are in constant interaction and their environment serves to "decohere" the quantum world—eliminate superpositions—to create the classical one we observe. Quantum mechanics has within it its own demise, and the process is too rapid to ever see. Zeilinger's group, which has tested decoherence, does not believe there is a fundamental limit on the size of an object to observe superposition. Superpositions should exist even for objects we see, similar to the infamous example of Schrödinger's cat. In fact, Gröblacher now spends his nights testing larger-scale quantum mechanics in which a small mirror is humanely substituted for a cat.

Brukner and Kofler had a simple idea. They wanted to find out what would happen if they assumed that a reality similar to the one we experience is true—every large object has only one value for each measurable property that does not change. In other words, you know your couch is blue, and you don't expect to be able to alter it just by looking. This form of realism, "macrorealism," was first posited by Leggett in the 1980s.

Late last year Brukner and Kofler showed that it does not matter how many particles are around, or how large an object is, quantum mechanics always holds true. The reason we see our world as we do is because of what we use to observe it. The human body is a just barely adequate measuring device. Quantum mechanics does not always wash itself out, but to observe its effects for larger and larger objects we would need more and more accurate measurement devices. We just do not have the sensitivity to observe the quantum effects around us. In essence we do create the classical world we perceive, and as

HERR PROFESSOR
Anton Zeilinger stands in front of the door to his office. To his left is a glass cabinet that holds the numerous medals he has won for tests of quantum mechanics.

Brukner said, "There could be other classical worlds completely different from ours."

Zeilinger and his group have only just begun to consider the grand implications of all their work for reality and our world. Like others in their field, they had focused on entanglement and decoherence to construct our future information technology, such as quantum computers, and not for understanding reality. But the group's work on these kinds of applications pushed up against quantum mechanics' foundations. To repeat a famous dictum, "All information is physical." How we get information from our world depends on how it is encoded. Quantum mechanics encodes information, and how we obtain this through measurement is how we study and construct our world.

I asked Dr. Zeilinger about this as I was about to leave his office. "In the history of physics, we have learned that there are distinctions that we really should not make, such as between space and time… It could very well be that the distinction we make between information and reality is wrong. This is not saying that everything is just information. But it is saying that we need a new concept that encompasses or includes both." Zeilinger smiled as he finished: "I throw this out as a challenge to our philosophy friends."

A few weeks later I was looking around on the IQOQI website when I noticed a job posting for a one-year fellowship at the institute. They were looking for a philosopher to collaborate with the group. ∞