The Quantum-Classical Transition on Trial:

Is the Whole More Than the Sum of the Parts?

by Hideo Mabuchi

There are some things they don't tell aspiring young scientists. Most of us assume that you work very hard to get through school, you get your degrees, and then, if you're very, very fortunate, you manage to land a job at a prestigious academic institution. You get your research group going, and then life is good, because finally you can get down to the business of chasing after all those shining Holy Grails of science—like grand unified theories of physics, or cures for cancer or AIDS.

Some people certainly do pursue the good life in that way. But others of us, for whatever reason, decide to follow a somewhat different career path. Rather than running out to the great frontiers of science, we get stuck back in the land of things that most people think are already understood. That's because somewhere along the line, we stumble across something that feels to us like a slight inconsistency or incompleteness. Maybe it's just some little detail, just a small wrinkle that needs to get smoothed over. But I think if you look back at the history of any science, you will find moments where something seems to be a small inconsistency until you tug on the loose thread, and everything unravels.

IMAGE NOT APPROVED FOR WEB USE

My topic here concerns one of those inconsistencies, the quantum-classical transition, which, in a sense, dates back to the historical debates between Bohr and Einstein. I had added "on trial" to the title, but then I began to wonder: What court is trying this case, and what are the charges? Then I realized that this trial goes on inside my own head. I'm working on the quantum-classical transition because I think it's interesting, but is it really the most important thing that I could do with my early career? Is this one of those questions that can lead to big things? Or is it just going to prove to be a little wrinkle? If you asked a roomful of physicists whether this was a good thing to study, many of them would just shrug their shoulders.

So in this "trial" the prosecution will charge that the quantum-classical transition is trivial and uninteresting. As the defense attorney, I want to try to

What happens where quantum and classical theories meet? If one is yellow and the other blue, would you get a green theory? Unlikely—they're too different to mix together smoothly.

convince you that it is, in fact, an important thing to look at. But at the same time, I also want to play devil's advocate and present the prosecutor's case. I'll try to give you both sides of the story, but I'm biased, of course.

First, I'd like to explain what is classical, what is quantum, and what we mean when we say that there's a transition between the two. We can talk about things that are big and things that are small and what theories we use to describe them. If we start in the macroscopic realm with a football field and come down from that size 100 times, we get down to about a meter, which is approximately the size of, say, a bicycle. Another 100 times brings us down to the centimeter scale, about the size of a dime. If I come down another 100 times, then I'm talking about a grain of sand or something the size of a fraction of a millimeter. And another factor of 100 brings us to the micron scale and things that we can't see with our bare eyes—things like living cells.

Now let's jump across a big gap and go smaller by a factor of 100,000, which takes us from the cell down to about the scale of an atom. And if we go down from the scale of an atom by another factor of 100,000, then we're talking about the atomic nucleus—the clump of protons and neutrons that sits inside every atom. At this scale, I think it's safe to say that we're truly in the microscopic realm of physical theory.

One of the surprising legacies that 20th-century physics has left us is the understanding that, as we describe things that occur in nature, we have to use two very different physical theories, depending on whether we're talking about things in the macroscopic realm (bicycles, coins, and grains of sand) or things that are down in the microscopic (atoms and their nuclei). Classical physics describes behavior of the former, behavior that you're familiar with in your everyday experience: balls bounce, sticks fly through the air when you throw them. Then there's quantum mechanics, which is kind of strange and fuzzy. Quantum mechanics describes the way that atomic and subatomic particles behave. This is a behavior that we never get to experience directly, simply because these things are just too small.

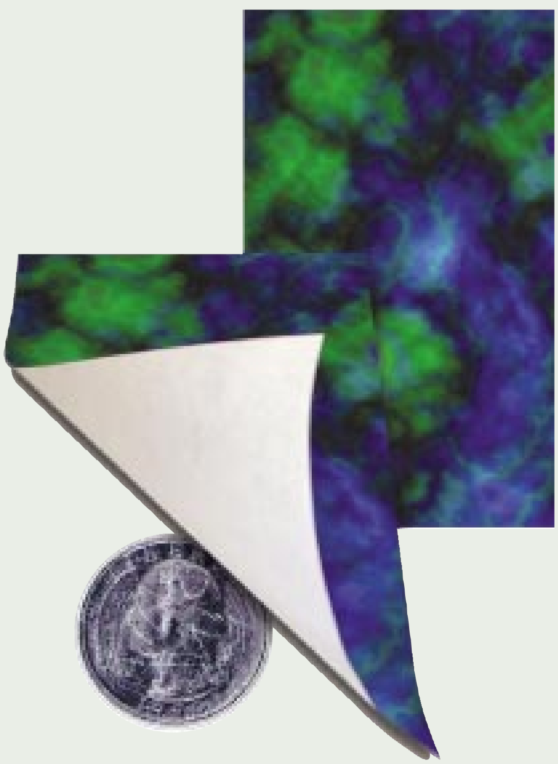
Yet there's kind of a no-man's land in the middle where things are slightly bigger than atomic size, but much, much smaller than living cells. The question is: What's going on in this no-man's land between quantum mechanics and classical physics? We're just starting to be able to do sophisticated experiments on systems that live in this range of sizes, and therefore we're well positioned to start asking concrete questions and provide concrete answers about this transition zone.

The counterargument would claim: But we're already able to design and construct and use very sophisticated technology that works in that range of sizes between atoms and cells. We have things like computer microchips at the micron scale, and even below that we have the techniques of biotechnology and genetic engineering. So, if we can already reach down there and do such amazing things, how can anybody claim that there's something mysterious about this transition zone?

Now, whatever you may think of technology (and who among us has never regretted the existence of e-mail?), it makes a compelling argument that we can use classical mechanics to compute and design things in the microscopic world. And, sure, we have to use different mathematics to describe or design in the truly microscopic realm, but there's nothing mysterious about that. We understand when we're supposed to use one theory and when we're supposed to use the other.

But these two theories are very different; they have a very different feel, a very different flavor. If I were to represent them by different colors, I could have a yellow theory that describes the behavior of small things and a blue theory that describes the behavior of large things. Then, you might expect some sort of mixture of the two in the middle: a green theory. But quantum mechanics and classical physics are so different—kind of like oil and water—that it's very difficult to understand how they might mix together in a smoothly graded transition from one to the other. So maybe this complicated mishmash of stuff in between *is* important to study.

Physicists often ask: Where are the frontiers of fundamental physics? And usually the answer is: at the extremes of the size scale. So, at the extreme microscopic end, we should be asking about the behavior of particles or systems that are much, much smaller even than atomic nuclei. This leads you to the study of things like string theory and



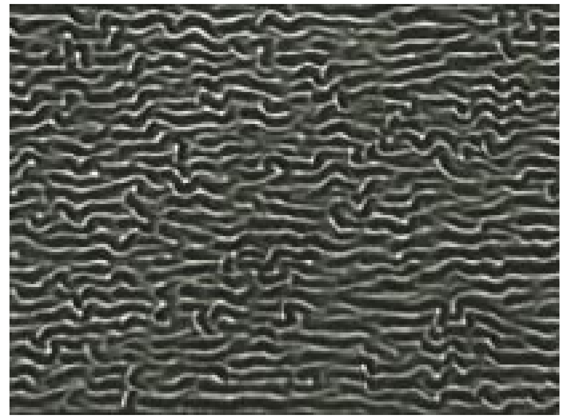
On the other hand, if we can understand exactly how it matches up to classical physics, I think we stand to learn a lot about what quantum mechanical theory really is and why it looks the way it does.

other sorts of grand unification theories. At the other extreme of the size spectrum, you could ask about things as large as the entire universe. At that point you're into astrophysics and cosmology. If those are the Wild West frontiers of physical theory, then this quantum-classical transition would be middle-class suburbia.

Now, it may turn out that, as you look into the great complexity of things that happen at this mesoscopic size scale between the microscopic and the macroscopic, you're just going to turn up a bunch of details. Maybe nothing fundamental happens there. On the other hand, if we can understand exactly how it matches up to classical physics, I think we stand to learn a lot about what quantum mechanical theory really is and why it looks the way it does. So, I'd like to give you a bit of a sense for the differences between the two in their basic features.

As an example, let's take a coin, a quarter. When I lay it on the table, I can place it heads up or tails up. Now, suppose I prepare this coin in some way that I don't describe to you: maybe I flip it and let it land as it may; maybe I spin it; maybe I ask somebody else to lay it heads up or tails up. Then I cover it with a card. I've done all this in the back room, so that you haven't been able to see what I've done. Now I bring the whole table out to you, and I tell you that I took an ordinary quarter and put it either heads up or tails up on the table and covered it with the card. If we're describing things in terms of classical physics, then I think it's fair to say that the coin is going to be either heads or tails. We don't happen to know which one of these two is the case, but it's either one or the other.

If we wanted to try to describe the state of this coin using quantum physics rather than classical physics, then I could have done something in the back room such that the coin was prepared as both heads and tails at the same time. It's not that it's one or the other and you just don't know which,



Quantum systems interact in a linear way—like the ripples on Millikan Pond. Macroscopic classical systems, on the other hand, are nonlinear—like the convection pattern in a more viscous fluid (far right); © Nonlinear Phenomena Group, LASSP, Cornell University, May 2002.

but in some sense you have to imagine that it's both. In the classical world your inability to predict what we're going to see when we lift up the card is strictly the result of not knowing something about the system. If I just whispered "tails" (and if you believed me), then you would know exactly what you would find when you lifted up the card. So, one very important feature of quantum physics that we believe is truly distinct from classical physics is that in quantum physics we can prepare things in a way such that there is intrinsic uncertainty about what's going to happen in the future. In classical physics, if you're uncertain about what's going to happen, it's only because there's stuff that you don't know.

Another distinction between the basic features of quantum and classical theory is that, as far as we understand, the dynamical behavior of quantum systems—the way they move and interact with one another—is always linear. On the other hand, we know that the motions of macroscopic things—like planets and asteroids or, say, fluids in a tank—can be highly nonlinear, which is a much more complicated kind of behavior.

This is a little hard to illustrate, but I'll try to give you an idea in terms of how waves behave in linear and nonlinear dynamics. Think about ripples propagating on the surface of a pond: the peaks and troughs are more or less stationary—they travel pretty much undisturbed until they hit some kind of obstruction, such as a rowboat or a twig sticking up out of the water. When they hit that twig or rowboat, they do something rather complicated: they diffract and change direction. But what's important is that these waves are propagating independently. They don't mess each other up; they're happy to coexist. This is linear behavior.

Nonlinear waves act very differently. You can see this complicated kind of behavior in the ripples or waves in a more viscous fluid. Even without any obstruction, the ripples propagate at different periods, and these different periods mess one another up. They look as if they're all tangling around one another. In quantum physics, the evolution of systems is simple and orderly in the sense of linear wave propagation, but when we make systems macroscopic, we're able to observe the kind of complex, nonlinear behavior illustrated by the second example.

This is why I think there seems to be something mysterious, or at least interesting, about the quantum-classical transition. The quantum world is kind of fuzzy (in other words, there is intrinsic uncertainty), but at the same time, systems evolve in a rather orderly way. On the other hand, in macroscopic systems, things are sharply defined (in the sense that uncertainty is never necessary), but the evolution of classical systems can be really complicated, even chaotic. Evidently, what's happening is that all the fuzziness and uncertainty at the small level in a way smooths itself out when you make things sufficiently large. We take these really small fuzzy globs that are evolving in an orderly fashion, and when we put enough of them together, for some reason everything crystallizes and becomes sharp while its dynamics becomes chaotic.

Why, exactly, does it work that way? Why doesn't it go in some other direction? And perhaps the most important question is: Why is this transition so robust? It doesn't seem to matter what kinds of quantum pieces we take or how we connect them together; as long as there are enough of them, we get this transition to classical behavior.

Now I'll turn to playing devil's advocate for a while. On the next page is a sequence of images. The first is a snowflake, a thing that you can pretty much see with your bare eye. You can't resolve very much without a microscope, but you can see it. The size scale here is something like a 10th of a millimeter. The next image, which was taken with an electron microscope, shows features

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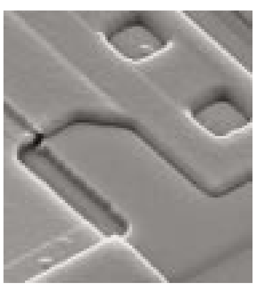


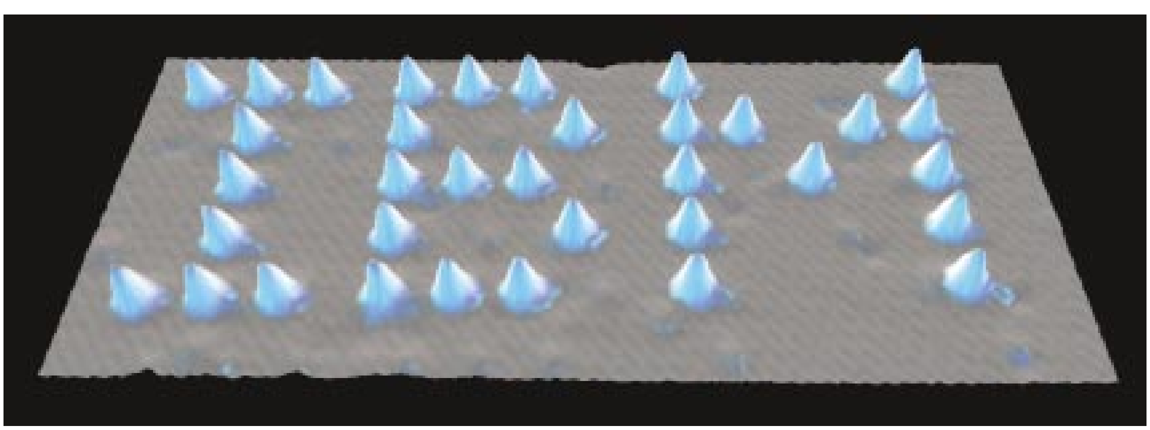
at the size scale of about 10 microns, or .01 millimeters. This is about the size of components on a computer chip, and it looks like a bar with holes in it sitting on a plateau of some kind. I could be showing you an aerial photo of a building, and it would look similar; there's nothing strange about it.

The last image was made by scientists at IBM's Almaden Research Center with a scanning tunneling microscope. The gray, fuzzy base is the very clean, flat surface of a chunk of nickel metal, and the conical, blue lumps are individual xenon atoms sitting on it. This microscopy technology enabled the scientists to pick up a bunch of atoms that they happened to find lying on the surface and rearrange them to spell out the name of the company. This wasn't generated as a computer graphic; it's a real microscope image of individual atoms. A single atom is something like a 10th of a nanometer, or .0000001 millimeters. This image could just as well be snow cones lying on the ground on a winter day. What is so quantum and strange about it?

I've been saying that microscopic systems—such as individual atoms—behave quantum mechanically. So, how is it that you can image those atoms sitting unmysteriously on the surface of the metal like blue lumps of clay? The reason is that, in order to get an individual atom to behave quantum mechanically, you have to put it in extreme isolation. Just the fact that this atom is sitting on the surface of a chunk of nickel is enough to induce a quantum-classical transition. We have to pick the atom up off that surface, suspend it in empty space—really, really empty space—and then allow it to do what it wants. The transition from this lump-of-clay-type behavior to something more quantum and mysterious has to do with how well isolated the system is. If we can isolate an atom sufficiently well so that nothing is touching it, nothing is poking or prodding it, there's no heat and no electromagnetic waves, then under these conditions the atom is happy and wants to do its quantum mechanical thing.

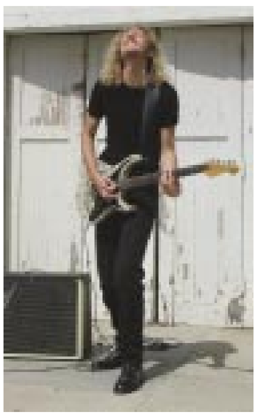
We might think of macroscopic behavior as being like a collection of musicians in a symphony orchestra all playing classical music together. But, perhaps, when nobody else is listening, one of those individual musicians might go off and play head-banging, heavy-metal music in private. Similarly, quantum systems in isolation behave in one way, but when we bring large collections of them together, they behave in a different way. There's a very sophisticated group dynamic that causes a different kind of behavior to emerge when individual people collect in large crowds and socialize and interact with one another. This is called an emergent behavior of collective systems.

Note that I've been saying that, when you take a single atom off the surface and put it in isolation, we expect it to behave in a quantum mechanical fashion. But I was very careful not to say that we expect to *observe* quantum mechanical behavior, because we're not even allowed to be looking at it. I think the fact that the act of measurement itself is very disruptive is actually a very big clue to what's going on in the quantum-classical transition. Somehow this act of measurement, of looking, we believe can force a transition from quantum mechanical behavior to classical. And our microscope image of the xenon atoms sitting on the nickel surface is really sort of a classical pro-



The snowflake at top left is on the scale of about a 10th of a millimeter. The components in the computer chip below it are about .01 millimeters. And the single xenon atoms (in blue) at left are about .0000001 millimeters. (Image courtesy of IBM Almaden Research Center.)

Musicians playing together, like the Los Angeles Philharmonic Orchestra shown here, exhibit the emergent behavior of collective systems. A single musician in isolation, behaving in an entirely different way, might be said to be acting quantumly.



jection of what these quantum objects are doing.

Everything we do in our lives (including every time I go into the laboratory and perform an experiment on individual atoms or individual photons) is classical and macroscopic. We go into the lab, we turn some knobs, an experiment happens, and data come out to us in the form of numbers or signals or whatever. The knob is never in two different positions at once; it's always in one or the other. All the interactions that I have with the experimental apparatus are all perfectly classical. And yet, somehow, by performing such experiments, we're able to convince ourselves that the behavior of the objects under study is actually qualitatively different. To me, that makes understanding the process of measurement a very important key in understanding the quantum-classical transition. The measurement theory has to look at microscopic systems, whose states start out being quantum, but the information that we get as a result of the measurement—the images from the microscope—has to be sensible in a classical way.

Remember the example of the quantum coin under the card. What actually happens when we finally make a measurement—when we lift up that card and look underneath? What would it look like to see a coin both heads up and tails up at the same time? When you look, you have to see one side or the other. There's no way that it can be both when you're sitting there staring at it. So, something about this act of measurement took a quantum precondition—being both heads up and tails up—and turned it into something that makes sense to us. And if we then put the card back over the coin and very carefully look again, it will be the same side up the second time.

Quantum physics imposes intrinsic uncertainty: We can't predict whether we'll see heads or tails because the coin is in both states at once. It's not just that we don't know enough; it really is completely unpredictable. A measurement made on a quantum system removes the uncertainty and forces something definite to happen. So in a sense, measurement is tied to this whole business about intrinsic uncertainty turning into classical uncertainty. Let's say that we looked at the coin once and found tails. Now we bring in somebody who was out of the room at the time and show him this card and say: "Initially we prepared a quantum state that was both heads and tails, and then we looked and we saw something and then put the card back." But we don't tell this new person *what* we saw. The uncertainty that this new person has about what's under the card is now a completely classical uncertainty, because they know that we had to have seen something definite. So they will now describe the state of the coin under the card as being either heads or tails. Even though it's a gross oversimplification to say that this is a quantum-classical transition, it does suggest that measurement plays an important role.

If I'm going to claim that measurement is the key to the quantum-classical transition, I have to try to explain what measurement has to do with the kind of group dynamics that causes classical behavior to emerge out of quantum behavior when you put enough stuff together. I have to be able to relate this to what happens when nobody is peeking. If we look back at the image of the individual atoms sitting on the nickel surface, it's a bit unsatisfying to think that the only reason that we see "IBM" is that we looked. (Or that, had we not been looking, this might say "Apple" or "Sun.") I think even a specialist in quantum physics would agree that it's probably safe to believe that even when you're not looking at them, those atoms are, in fact, sitting there like little lumps of clay spelling out "IBM."

But why is it exactly that when you put lots of small systems together, somehow collectively they decide that they need to behave classically? This is a profound idea that we don't really understand very well. But the advent of the laser about 30 years ago gave us a new way of thinking about the problem and clarifying the relationship between measurements made on quantum systems and emergent group dynamics. The details of this theory (which was originally developed largely for the purpose of modeling masers and lasers) are beyond the scope of this article, but I'll try to give you a sense for our modern understanding. Using the coin-and-card example, we say that the state of being both heads and tails at the same time is a *coherent* mixture of the two possible states, whereas heads *or* tails is an *incoherent* mixture. *Decoherence* is the term we use for describing the process of turning one of those kinds of uncertainty into the other, such as by looking underneath and then asking somebody else to do so.

Decoherence doctrine offers us a way of understanding all this stuff. We can say that, even when nobody is looking at these xenon atoms on the nickel surface, any physical environment that these atoms happen to be coupled to is, in a way, continuously measuring where they are. So, even though the individual atoms are sitting on what looks to us like a smooth surface, that metal surface is made up of lots and lots of atoms. A chunk of metal that size would have something like a million billion billion atoms or more. Decoherence doctrine says that the xenon atoms are sort of pushing off against the nickel atoms. And when one atom starts to jiggle, it shoves everybody else around. So coupling can be viewed as the atoms in the metal making continuous measurements of the xenon atoms, asking at every point in time: "Where are you?" They force the xenon atoms to stop exhibiting quantum behavior and decide where they're going to be.

Now, as systems get larger and larger, it becomes harder and harder to isolate them in order for them to behave quantum mechanically in the first place. And, while we know how to isolate a single atom, we have no idea how to pick up a baseball and levitate it in empty space, completely isolated from everything else in the universe. The decoherence process happens faster and faster, and more and more inevitably, as we start considering larger systems.

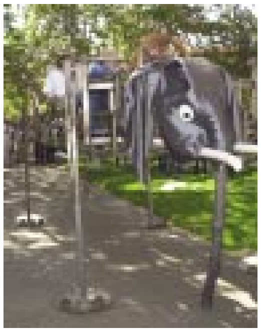
So, for people who work in decoherence (and I have to admit that I'm one of them), the doctrine explains the quantum-classical transition in the sense that we can at least point to a few examples where we feel that we understand how quantum uncertainties get turned into classical uncertainties. And maybe in a few cases we understand where nonlinearity comes from. But, going back to our "trial" again, does this make quantum-classical transition an important and fundamental field or just a set of little quantitative wrinkles?

> "Theory is way ahead of experiment. It's like Hannibal trying to cross the Alps. We'd really like to run ahead and see what's on top, but we have all these elephants to deal with." —*Jeff Kimble*

One powerful argument for the defense is the field of quantum computing. Of great interest in the past five years and a very active topic of research here at Caltech, the idea is that it may be possible to build computing devices in which the little logic things—the chips, the elements—inside the computer behave according to quantum physics and not classical physics. These would be computers made not of chips and resistors and logic gates, but of individual atoms somehow coupled together. This is a very exciting idea, and many people around the world are chasing after it. A large enough quantum computer would be able to solve mathematical problems that a regular computer could hardly begin to solve. So far, only baby steps have been taken in terms of actually building something or even writing down theories about how it might work. It's probably a good 20, 30, or 50 years off before we really have any hope of building such a thing. Nonetheless, we're starting to do the basic science in this field.

You see it in the respectable science journals (one famous article published in *Physics Today* bore the title, "Quantum Computing—Dream or Nightmare?"), and the popular press has picked it up as well. One quote that I really like came from my thesis adviser, Jeff Kimble (the Valentine Professor and professor of physics), and appeared on page 2 of the February 18, 1997, *New York Times* as the Quotation of the Day. On progress in the field of quantum computing, Jeff said: "Theory is way ahead of experiment. It's like Hannibal trying to cross the Alps. We'd really like to run ahead and see what's on top, but we have all these elephants to deal with." Jeff is referring to trying to build something that's fairly large and make it behave quantum mechanically. We have to fight against this process of decoherence, and the things we think we already understand about the quantum-classical transition suggest to us that this may be a losing battle. As we try to make a quantum computer larger and larger, so that it can solve bigger and bigger problems, we may find it harder and harder to prevent this thing from just making a transition into classical behavior. Then we would just have a very expensive version of an ordinary old computer.

Despite the problems, the reason why people are staying in this field is that there have been some remarkable developments in the theory of quantum computing—largely here at Caltech—called fault-tolerant architectures. It works in somewhat the same way that classical computing



Not exactly Hannibal and the Alps—or quantum computing—but Caltech students have dealt with experimental elephants, as demonstrated here. The walking (sometimes) mechanical elephant appeared on Ditch Day, May 22.

devices deal with small errors. You may have stored some information, but when the disk drive reads it off, it occasionally makes some errors in reading all the zeroes and ones. You rarely notice this because there are mathematical procedures for correcting those errors. With quantum computing devices, we're not talking about errors per se, but about decoherence problems, which are very much like errors in that they influence the computer to behave incorrectly. A team led by Professor of Theoretical Physics John Preskill was able to show that if you build the architecture of a quantum computer in a very specific way, or in one of a class of specific ways, it's possible to correct the kinds of errors caused by decoherence.

Decoherence theory tells us that, when we take lots of tiny quantum parts and connect them together in a general way, we can pretty much expect to get a classical whole out of them. But the lesson that we think we're learning from the theory of fault-tolerant architectures is that it *is* possible to find very specialized and specific configurations of parts inside a quantum computer such that you can resist that transition to classical.

We already know of a couple of ways to try to do this, but we don't know whether the schemes that people have come up with so far are the best possible ones. Are they, in fact, really clumsy schemes, and if we look harder will we actually find much better ones? Now, the fact that we don't even understand whether the schemes that have been suggested so far are good or bad tells you that we're just at the stoop and trying to get into the door of understanding what's going on in there.

Back to the trial: the prosecution has been trying to argue that the quantum-classical transition is just an estuarial zone between two very well understood theories. We know about classical physics; we know how to compute with it; we can design technology at the nanoscale. And we know about quantum mechanics; we know when we're allowed to use it. If there's an incomplete understanding of the stuff in the middle, it doesn't matter much.

The good thing about being on the defense is that you don't necessarily have to make a compelling case. You just need to introduce a reasonable doubt that the prosecution's argument is not airtight. I have tried to give you some examples of reasons why I think our understanding of this transition is incomplete in some really fundamental way, and that many interesting questions remain completely unanswered. And now we have a couple of leads on how we're supposed to study things in this region. We think that quantum measurement (this is what my group does) is going to be an important key, and we understand a little bit of what's going on in the now traditional theory of decoherence. Defining what happens in the quantum-classical transition may be critical to building a quantum computer that will resist that transition. □

Hideo Mabuchi came to Caltech as a grad student in 1992, after earning his AB from Princeton. When he finished his PhD (1998), he stayed on as assistant professor of physics and became associate professor in 2001. He is currently associate professor of physics and control and dynamical systems. For his work in quantum optics and atomic physics and in optical biophysics, he has been named a Sloan Research Fellow and an Office of Naval Research Young Investigator, and has received a $500,000 "genius" grant from the John D. and Catherine T. MacArthur Foundation (class of 2000). Mabuchi was listed by Discover *magazine among the "Twenty Scientists to Watch in the Next Twenty Years." This article was adapted from his Watson Lecture of last November.*

(The quantum musician on page 37 is Ulrik Beierholm, grad student in Computation and Neural Systems.)

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