THE JOURNAL OF THE COMMITTEE ON MONETARY AND ECONOMIC REFORM

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$3.95

Vol. 24, No. 8 • AUGUST 2012

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Publications Mail Agreement No. 41796016

Climate Change Opens Up Arctic Fisheries — But Should Canada Cut Bait?

Northern communities need the business, but experts fear ecological disaster as Ottawa halts research.

By Peter Christie, The Globe and Mail, July 21, 2012

Pangnirtung, Nunavut – Pangnirtung, a solitary hamlet of 1,500 clinging to the granite mouth of Pangnirtung Fjord in Baffin Island's Cumberland Sound, seems like a quintessential, isolated Arctic community. Low, weather-battered board homes punctuate its dirt streets. Some are literally cabled to the ground against the wind. Often, they are cramped with people.

"Overcrowding is a big problem," Mayor Sakiasie Sowdlooapik tells me, speaking in his small office in a narrow corridor of the community centre. Not many here have jobs – in a typical year, six out of 10 need government support to get by.

But what separates Pangnirtung from the all-too-familiar tale of Northern underdevelopment is this: It is one of the centres of an improbable but fast-emerging Arctic fishing industry.

As one of the world's largest fish and seafood exporters (a business worth $3.9 billion in 2010), Canada might be unique in that the potential fisheries along almost three-quarters of its coastline are largely untapped and unexplored. Until recently, those Arctic marine shores kept many of their undersea secrets well hidden beneath metres-thick ice and at harsh, impassable distances.

Now, climate in the Far North is warming twice as quickly as on the rest of the planet and formerly impenetrable seas are opening up like so many ice boxes.

Pangnirtung was once supported by sealing, but after the market for fur fell apart in the 1980s, experts from Greenland were brought here to teach the former sealers to fish through the ice for turbot, a commercially valuable fish with which few Inuit had any experience. Before long, there were not only fishers here but the largest fish-processing plant in Nunavut, which currently boasts about $4 million annually in sales, mostly to China.

Elsewhere in the Eastern Arctic, other fisheries for turbot, northern and striped shrimp and trout-like Arctic char have been gathering momentum. Turbot catches in Davis Strait and Baffin Bay have almost tripled in the past 15 years. And in some places, test fisheries have also been tried for clams, starry flounder, scallops and snow crabs.

Life has improved, Mr. Sowdlooapik says, but it's not enough: "We need better harbours. We need better off-loading ports. We need bigger boats to bring in more fish of bigger value."

As fishing grows, however, government scientists – the people who are supposed to

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Economic Reform (ER)
(ISSN 1187–080X) is published monthly
by COMER Publications
27 Sherbourne Street North, Suite 1
Toronto, Ontario M4W 2T3 Canada
Tel: 416-924-3964, Fax: 416-466-5827
Email: comerpub@rogers.com
Website: www.comer.org

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PRINTING AND DISTRIBUTION
Watt Solutions Inc., London

Printed in Canada on recycled paper.

Fisheries *from page 1*

be managing the fish – are scrambling to keep up. Like many undersea Arctic ecosystems and creatures, marine life in Cumberland Sound has remained inscrutable…to researchers.

Meanwhile, government cuts to fisheries science have raised concerns that managers are too much in the dark about how sustainable the fishery might be.

And then there are the sharks. The sound is home to many Greenland sharks, the world's second-largest carnivorous sharks (after the infamous great white), and large numbers of them are accidentally hooked on Pangnirtung's turbot lines, lured by the bait.

"When they are not too tangled, sometimes you just loosen them and let them go," Mr. Sowdlooapik says. "When they are tangled, you have to take them out" – that is, kill them.

The shark is a "near threatened" species on the Red List of the International Union for the Conservation of Nature (IUCN). It's hard to tell, through the Arctic ice, how dire their peril is and if fishing is making it worse.

It's a microcosm of the problem with having a flourishing "third coast" commercial fishery in Canada. Where Ottawa and Nunavut see the promise of a key piece in the long-frustrating puzzle of Arctic economic development, several leading academic researchers see potential of a different kind – the likelihood of ecological disaster.

The Arctic fishing industry is small so far, with landings worth about $75 million annually, compared with $1.4 billion on the East Coast in 2009 and $250 million in the West.

But the government of Nunavut – the vast, 13-year-old territory that occupies much of the Canadian Arctic – describes fishing as a vital pillar (alongside mining, tourism, and cultural industries) of its economic-development plan.

"We've got a significant fishery in the offshore right now, and it can grow," Wayne Lynch, the Nunavut Environment Department's director of fisheries and sealing, says.

Mr. Lynch, a lead author of the 2005 Nunavut Fisheries Strategy, argues that the territory's commercial fishing is "at a crossroads" where more investment and infrastructure is needed to continue its impressive growth.

That is why Nunavut is pushing to build its own deep-water port (possibly at Qikiqtarjuaq on Baffin's northeast coast) to offload and service its offshore fleet, which now must travel to Greenland to find large harbours. It also continues to lobby for bigger quotas and to search for new marketable fish to catch.

"No one thought 10 years ago that we'd be where we are," Mr. Lynch says, buoyantly. "It's got a long way to go yet too."

Oceanography professor Louis Fortier bristles at that suggestion. "In my opinion, there's no Klondike there," he says from his desk at Laval University. "I know they think they are going for the gold mine, but they are wasting their time."

Prof. Fortier, who is among Canada's pre-eminent Arctic marine scientists, leads the $110 million national network known as ArcticNet. He spearheaded efforts a decade ago to retrofit the Amundsen, a Canadian Coast Guard ship, as a dedicated research icebreaker for the North.

He is also one of a number of researchers who want to see large-scale commercial fishing in the ecologically delicate seas above the 60th parallel stopped before it grows.

"We need a moratorium on any development of big fisheries in the Arctic," he argues – leaving only traditional, small-scale fishing. "[But] with the usual procrastination of the DFO [Department of Fisheries and Oceans] and the federal government, it has never been done."

Nunavut's fishing ambitions do appear to be out of step with other jurisdictions in the North American Arctic. In 2009, for instance, Gary Locke, then US commerce secretary, cited the need for a "precautionary approach" when he announced a US ban on all new industrial-scale fishing north of Alaska for the next few years.

More recently, 2,000 scientists signed a letter urging a similar moratorium in the international Arctic waters just beyond Canada's jurisdiction.

And last year, the Inuvialuit of Canada's Western Arctic pushed for – and got – an agreement with Ottawa to effectively declare the vast Beaufort Sea off-limits to commercial fishing in the near term. "The Inuvialuit saw examples around the world of collapses of commercial fisheries because of overfishing," explains Burton Ayles of the Joint Fisheries Management Committee that oversees Western Arctic fisheries.

Dalhousie University marine-biology professor Boris Worm has studied many of those collapses. In the journal Science a few years ago, Prof. Worm predicted that large-scale fishing would drive the last of the world's commercial fish and seafood stocks to ruin by 2048. He is less pessimistic now ("the situation is more complex"), but he continues to fear for sensitive environments such as the Arctic.

Knowledge gaps are common, Prof. Worm says, and fishing boats are sailing right through them. Greenland sharks, for instance, are "virtually unknown in their life history," he says. "One pregnant female has been observed in all of science."

A similar lack of life-cycle information applies to many other creatures, from obscure sea sponges to the turbot, char and shrimp targeted by the industry.

"If this was a very abundant, very productive ecosystem with a high resilience to disturbance, I would be less concerned," Prof Worm says. "But, from all we know, these tend to be very complex, poorly understood, somewhat fragile ecosystems and resources, and I think we either do good science on them or we leave them alone."

There, especially, is the rub: Fisheries and Oceans Canada, responsible for managing Arctic fish, has suffered a series of deep budget cuts recently – including a $79.3 million rollback over the next three years announced in March. Many are concerned federal research is now languishing.

"A DFO colleague just a few weeks ago told me in these very words, 'DFO science, as we know it, is dying,'" Prof. Worm says. "And to me, this is the alarm bell: Canada certainly is very good at saying all the right things, but in the absence of information, this is not quite possible. You need to understand something before you can manage it, and the Arctic is very poorly understood."

From her Fisheries and Ocean Canada office in Winnipeg, Michelle Wheatley, director of science for the central and Arctic region, fashions her words carefully: "I'm not in a position or authorized to enter into discussions on the budget cuts, but I can say that science is essential to the business we do, and we are continuing to build our scientific knowledge."

Managing fisheries in the Arctic follows a government protocol known as the Emerging Fisheries Policy, Dr. Wheatley says. That means regularly monitoring target fish as well as other species. Ongoing research includes annual multi-species surveys in Baffin Bay and Davis Strait as well as gathering shrimp data and char catch numbers from fishing vessels or by sampling. It adds up to a go-slow approach to fisheries development, she explains.

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PART 2 OF AN EXTENDED EXCERPT

Quantum Mechanics: The Physics of the Microscopic World

Course guidebook by Professor Benjamin Schumacher, Kenyon College. Published by The Great Courses, Chantilly, Virginia, 2009.

Our Comment

In preserving the techniques of quantum analysis, one must ask where does "quantitative" analysis leave the world and its future. In Greece itself the questions of Socrates and the answers of his pupils – notably of Plato – one cannot expect a simple answer, but must look in multiple directions for due answers including even the phase of the moon. Without such searching it is simply impossible to prevent world society from going up in blood and smoke.

The wisdom of Plato would be mocked if it were left verboten *– today the case in every country of the world including Greece itself.*

The first part of this extended excerpt ran in the July 2012 issue of ER.

W.K.

Entangement, Lecture 15

In this lecture, we're going to talk about the quantum mechanics of composite systems, systems that are composed of 2 or more individual particles.... We skimmed this topic for our discussion of identical particles.... [Now] we're going to follow this road to a different destination. It's going to lead us to the idea of quantum entanglement...a key feature of quantum world.

As mentioned above, a composite system composed of 2 or more particles can have quantum entanglement." What states are possible for a pair of particles? Assume that they are distinguishable in some way, so that we can designate them #1 and #2. "Simple states" arise when each particle has a state of its own. If the state of #1 is $|U\rangle$ and the state of #2 is $|V\rangle$, then the state of the composite system is just $|UV\rangle$. (Note that $|U\rangle$ and $|V\rangle$ do not have to be basis states.) Simple states work like multiplication and thus are sometimes called "product states." If particle #1 is the state $|U\rangle$ and particle #2 is in the state $a|V\rangle + b|W\rangle$, then the composite state is:

$$|U\rangle \text{"times"}\, a|V\rangle + b|W\rangle = a|UV\rangle + b|UW\rangle$$

This fact is called the "composition rule" and is the last of basic rules of quantum mechanics.

Not every state of the 2 particles is a simple state. The ones that are not are "entangled states," or states with entanglement. (We may also say that the particles themselves are entangled or have entanglement.)

Entangled particles display some interesting features. First, if 2 particles are in an entangled state, neither particle has a definite quantum state of its own, but the pair does. This is a strange situation. In classical physics, every particle has its own state-its own position and momentum-no matter what. Also, if we measure 1 particle, update rule II applies at once to both particles, even if they are far apart.

A very useful example of entanglement is a pair of spin-½ particles in a total spin 0 state. The total spin 0 state looks like this: $s|\uparrow\downarrow\rangle - s|\downarrow\uparrow\rangle$. (The minus sign is important.) We can arrange for 2 spins to be in such a state. For example, the spin of the electrons in a helium atom in its ground state are in a total spin 0 state.

The total spin 0 state has 2 key properties. First, for any spin-axis measurement on 1 spin, the probability of either result is always ½. Second, if we measure both spins along the same spin axis, we must always get opposite results, since the total spin is 0. For example: If we measure the z-axis on spin #1 and get the result $|\uparrow\rangle$, we must immediately assign the state $|\downarrow\rangle$ to spin #2; if we measure the x-axis on #1 and obtain $|\rightarrow\rangle$, we must immediately assign the state $|\leftarrow\rangle$ to #2; and so on.

Quantum entanglement became the focus of the last stage of the Bohr-Einstein debate. After 1930, Einstein accepted that quantum mechanics is consistent. However, he still did not regard it as a complete description of nature. Einstein thought that there must be things, in nature that are real but are not described by quantum mechanics. In 1935, Einstein, Boris Podolsky, and Nathan Rosen (EPR for short) wrote one of the most consequential papers in history: "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?"

In this paper, EPR called attention to the strange nature of quantum entanglement.

Before a measurement on spin #1, spin #2 does not have a definite state. Particle #2 gains a definite state instantly-even if it is far away-when the measurement is made on #1. (Einstein called this "spooky action at a distance.") How do we know when something is real? EPR gave their answer: If we can predict something about a system without interacting with the system in any way, then that something must be real. Quantum mechanics says that no spin can have definite values of x and z at the same time. In quantum physics, the values of x and z cannot simultaneously be real.

The EPR experiment worked like this: 2 spins are created in a total spin 0 state. If we measure x on #1, then we know the value of x on #2. (It must be opposite.) If we measure z on #1, then we know the value of z on #2. (It must be opposite as well.) Without "touching" spin #2 in any way, we can determine either its x value or its z value. By the EPR criterion, both x and z must be real. Therefore, quantum mechanics is not a complete description of nature!

Bohr's reply was rather tricky and hard to understand. He argued that we must regard the 2 entangled particles as a single system, not 2 systems. The x and z measurements on #1 are still complementary. We cannot make both measurements at once, and so we cannot actually know both x and z for particle #2 at the same time. If we measure 1 of the 2, we cannot say what would have happened if we had measured the other. (Recall Peres's motto: "Unperformed experiments have no results!") There is no "action at a distance," as Einstein called it. But there is a sort of "complementary at a distance," in the entangled system. And this knocks down the EPR argument. Einstein, however was not convinced.

The final round of the Bohr-Einstein debate seems inconclusive. Among the remaining questions are these: Is the EPR argument correct? That is, does quantum mechanics demonstrate its own incompleteness? Do quantum variables like x and z really have definite (though hidden) values? Can a particle affect another instantaneously at a distance? Or is Bohr's subtle rejoinder correct?

Questions to consider:

1. A coin is sliced into 2 thinner pieces, each piece bearing 1 of the coin's faces. The 2 half coins are randomly pit into 2 envelopes and mailed to 2 separate locations. Before an envelope is opened, we do not know whether it contains the head or the tail. But afterward we know the contents of both envelopes. What does the EPR argument say about this situation? How are the properties of the total spin 0 state different from the half coin experiment?

2. Write the total spin 0 state $s|\uparrow\downarrow\rangle - s|\downarrow\uparrow\rangle$ in terms of the basis states $|\rightarrow\rangle$ and $|\leftarrow\rangle$. You will need to write $|\uparrow\rangle$ and $|\downarrow\rangle$ in terms of $|\rightarrow\rangle$ and $|\leftarrow\rangle$, then use the composition rule. This calculation involves a bit of work, but the final result is satisfying?

Bell and Beyond, Lecture 16

Bohr responded to the EPR argument.… Based on this critique, we concluded that the EPR argument was not airtight. So the matter stood for almost 30 years. Then in 1964, John Steward Bell, an Irish particle physicist, reconsidered the EPR argument, and thereby changed the world.… He showed that the physics of quantum entanglement actually leads us to a very different conclusion about the nature of reality.

In his paper, John Bell carefully analyzed the EPR argument. He noted that it includes 3 identifiable propositions about the world. One proposition is that quantum mechanics correctly predicts the behavior of entangled states-specifically, the total spin 0 state of 2 particles, which we can check by experiment. Another proposition pertains to hidden variables; it says that the results of measurements are actually predetermined. We use probabilities only because we lack detailed information about the hidden variables that determine the results. The third proposition relates to locality. Specifically, the behavior of any particle is locally determined-that is, it is governed only by the particle's own variables and the immediate circumstances, including any measurement apparatus. According to Bell, the EPR argument can be summarized this way:

Entanglement + locality = hidden variables

Bell decided to try something different: Assume both locality and hidden variables, then study the consequences for entanglement.

Bell derived an inequality that any "local hidden variable theory" must satisfy. We imagine 2 spins: #1 and #2. On #1 we measure spin components A or B, and on #2 we measure spin components C or D. This gives us 4 possible joint measurements: (A,C), (A,D), (B,C), and (B,D). Let $P(A = C)$ be the probability that A and C measurements give the same results (either both +½ or both –½). In a similar way, define $P(B = D)$, etc.

Assume that there are hidden variables and that locality holds. A particular example illustrates Bell's argument. A, B, C, and D all have values every time we do the experiment, even though we only find out some of the values. Furthermore, by locality, the value of A on #1 does not depend on whether we are measuring C or D on #2. Assume the following: $P(A = C) = 0.85$, $P(C = B) = 1.00$ and $P(B = D) = 0.85$. What can we say about $P(A = D)$? Our assumptions mean that B and C are always the same, so A agrees with B 85% of the time. (We can conclude this even though we never measure both A and B together.) If B agrees with D 85% of the time, then A must agree with D at least 70% of the time. Therefore, $P(A = D) \geq 0.70$. This is a special case of Bell's inequality.

Quantum systems can violate Bell's inequality. We create our 2 spins in a total spin 0 state. The probability of agreement between 2 spin measurements A and C depends on the angle α between the axes. By applying the quantum rules and what we have already learned about spin, we arrive at the following table:

α	0°	45°	90°	135°	180°
$P(A = C)$	0.00	0.15	0.50	0.85	1.00

We can choose the 4 spin axes so that the AC angle is 135°, the BC angle is 180°, the BD angle is 135° and the AD angle is 45°. This will satisfy our assumptions about $P(A = C)$, $P(C = B$, and $P(B = D)$. However, quantum mechanics predicts that $P(A = D) = 0.50$, which is less than 0.70. Quantum entanglement violates Bell's inequality!

Bell finds the fatal flaw in EPR. The 3 propositions – entanglement, hidden variables, and locality – cannot all be true at the same time! Therefore, the latter 2 cannot imply the first. Experiments confirm quantum mechanics, even when the 2 spins are very far apart. Therefore, we must either give up determinism (hidden variables), or we must imagine that entangled particles can influence each other instantaneously over great distances (faster than the speed of light), or both! Bohr would have said that the hidden-variables assumption is flawed because of complementarity. Bell himself preferred to say that quantum mechanics was "non-local."

A postscript: Einstein died in 1955, Bohr in 1962. Neither of them got to see the surprise twist in the debate about EPR.

Questions to consider:

1. In a classroom simulation of the Bell experiment, 2 students are given separate

instructions and sent to opposite ends of campus. The students then answer yes or no to questions posed to them. Student 1 is asked either question A or question B, and student 2 is asked either question C or question D. After doing the experiment many times, we find that the answer to A and C agree 85% of the time, as do the answers to B and D, while B and C answers always agree. What can we say about how often A and D agree?

2. Now suppose the 2 students are provided with radios so that they can coordinate their answers "instantaneously" at the distance. Can we draw the same conclusion? Is this a fair representation of the Bell experiment?

All the Myriad Ways, Lecture 17

Now [we're] going to turn our attention to another important part of quantum theory. We're going to talk about a new way of looking at the theory. It's a way that has proved to be terribly important in making detailed theories about elementary particles in the present day.

In the 1940s, Richard Feynman devised a startling new way to look at quantum mechanics. The new perspective that he provided stemmed from his answer to the question of how an electron travels from point A to point B. Specifically, he looked at the question of what determined the probability $P(A \rightarrow B)$ that an electron makes the trip. According to Schrödinger, who also had looked at this question, the electron's quantum wave travels through space, and the intensity of the quantum wave determines the probability of finding the particle there. Must we imagine that the electron somehow "solves" Schrödinger's wave equation? That would be a pretty smart electron!

Feynman says this is how it works:

- Write down all of the possible ways (paths) to get from A to B.
- Assign an amplitude to each path according to a simple rule. (We will skip the details.)
- Add up all of the amplitudes for all paths to get a total amplitude $A(A \rightarrow B)$. This adding of amplitudes may involve a lot of constructive or destructive interference.
- The total probability is just $P(A \rightarrow B) = |A(A \rightarrow B|^2$.

In this scenario, the electron does not have to be smart; it simply tries everything, and the amplitudes add up. This is called the "sum-over-histories" approach to quantum mechanics. The general idea of the sum-over-histories approach can be illustrated by our favorite example, the photon in a Mach-Zehnder interferometer.

Feynman's idea turned out to be extremely useful for working out the quantum interactions between electrons and light – the field of quantum electrodynamics (QED). He drew little cartoons to represent possible histories of electrons and photons. These are called Feynman diagrams. In these cartoons, time points upward – the future is at the top, the past at the bottom. Solid lines pointing up represent electrons. Solid lines going down represent "positrons," which are antiparticles to electrons. Positrons and electrons have the same mass and spin but opposite electric charge. In QED, a positron is an electron going "backward in time." Wavy lines represent photons. These are either "real photons" (wavy lines that come out of the diagram), which can be detected, or "virtual photons" (wavy lines that begin and end within the diagram), which can be detected, or "virtual photons" (wavy lines that begin and end within the diagram), which are not directly detectable. A "vertex" represents an event where a photon is created or destroyed by an electron or a positron. Feynman gave a mathematical rule for assigning amplitudes to each diagram. More complex diagrams (with more vertices) make smaller contributions, so we can often just consider the simplest ones.

QED gives a quantum description of the electrical repulsion between electrons. The simplest diagram involves an exchange of a virtual photon. Where does the energy for this photon come from? A usable though imperfect answer is that we can "borrow" energy ΔE for a time Δt without violating any laws, provided we stay below the "uncertainty limit. "Thus $\Delta E \Delta t < h$. Virtual photons can be exchanged even over long distances because photon energy can be as small as we like. However, the resulting force will be weaker at large distances.

QED also describes the collision of a photon and electron, called "Compton scattering." There are several possible diagrams for this process, and all contribute to the quantum amplitude for it. The most important ones have 2 vertices. In these diagrams, the electron may absorb the incoming photon, then emit the outgoing photon. It may also emit the outgoing photon first, then absorb the incoming one. Alternatively, the incoming photon may create an electron-positron pair, and then the positron annihilates the incoming electron.

To get more precise results in QED, we must simply include more and more complicated diagrams in the calculation. There might be a lot of these. Electrons continually emit and absorb virtual photons. This changes their observed properties. Mathematically, the process can lead to an apparently infinite result. However, it the not-quite-magic procedure called "renormalization," the infinities can be persuaded to cancel out, leaving only the finite answer.

QED is the most accurate physical theory ever developed. It predicts certain phenomena, like the magnetic properties of the electron, to about 1 part in 1 trillion (1 in 10^{12}). QED is also the prototype for modern theories of fundamental forces. All forces are carried by the exchange of virtual bosons of one sort or another. For nuclear forces, the exchanged particles have mass, which means there is a lower limit to the energy ΔE that must be "borrowed" to make them. These forces act only over very short ranges.

Questions to consider:

1. Feynman regarded his sum-over-histories way of thinking as simply an extension of the quantum 2-slit experiment. Give an explanation of that experiment in Feynman's terms.

2. Consider the Compton scattering process, in which a photon "bounces off" an electron. Draw several Feynman diagrams for this process. How many different diagrams can you find with exactly 3 vertices? Four vertices?

3. Japanese physicist Hideki Yukawa proposed in the 1930s that the nuclear force between protons and neutrons is carried by particles. From the observed short rage of the nuclear force, he deduced that these particles had to have about 200 times the mass of an electron. Explain how such a deduction was possible. (Yukawa was proved correct a decade later with discovery of the pi meson, or "pion".)

Much Ado about Nothing, Lecture 18

Swarms of virtual particles are present in these [Feynman] diagrams. They come and go unobservably, underneath the limit set by the time-energy uncertainty principle.... This time we're going to analyze what is going on in so-called "empty space," and we'll find that the quantum mechanical answer is quite a lot is going on; and that this fact, that there's a lot going on where nothing appears to exist, has enormous consequences.

At its absolute minimum energy, a quantum system still has some energy in it. This is called "zero-point energy." One way to thing about this idea is to consider both classical and quantum pendulums. A classical pendulum has energy both in its motion (kinetic energy) and by virtue of its displacement from the bottom (potential energy). If it is exactly at rest at the bottom point, its energy is zero, This cannot be true for a quantum pendulum. To be exactly at rest at the bottom point, we would need both Δx and Δp to be 0. The uncertainty principle forbids this. Even in its ground state, the lowest energy level, the quantum pendulum has a zero-point energy of $hf/2$, where f is the pendulum's frequency. This is half of a "quantum of energy" for the oscillating system.

Zero-point energy can make a real difference. One example is the strange difficulty of freezing helium. Almost any substance will freeze if it is made cold enough. Molecules are slightly "sticky" due to the van der Waals force, so if they are moving slowly enough they will stick together and be "frozen" in place. Helium condenses into a liquid near absolute zero, helium atoms have enough zero-point energy to prevent freezing. It is possible to freeze helium, but only by imposing very high pressures to make up for the lack of "stickiness" between the atoms.

Even "empty space" – the vacuum – has quantum zero-point energy. In the electromagnetic field, energy comes in the form of photons. Even with zero photons – the vacuum state – the electromagnetic field has zero-point energy. The vacuum is filled with electromagnetic fluctuations at all frequencies. Spontaneous emission of a photon from an atom can be viewed as "stimulated emission" by the quantum fluctuations of the vacuum.

In 1948, Hendrik Casimir discovered a way to observe vacuum energy directly. The presence of metal objects slightly reduces the number of ways that the vacuum can fluctuate. The vacuum state is distorted to "fit around" the objects. Between 2 parallel metal plates, the vacuum fluctuations are reduced. Therefore, there is less vacuum energy (les "nothing") between the 2 plates than there is outside of them. This leads to a tiny attractive force between the plates called the "Casimir effect." This effect was soon detected experimentally, but the first really accurate measurements had to wait for the 1990s.

Vacuum energy may have cosmic implications. In 1998, cosmologists learned that the expansion of the universe is actually getting faster over time. Not only are galaxies getting further apart – an aftereffect of the Big Bang – they are doing so at an increasing rate. This was a surprise – simple gravity would suggest that the expansion should be slowing down, not accelerating. The physical cause of acceleration is called "dark energy" – "dark matter," which is matter of an unknown type that is also present but ahs a different effect.

One leading hypothesis is that the dark energy is quantum vacuum energy, the energy of empty space. As space expands, more dark energy appears, driving the expansion faster. One major difficulty with this idea is that, if we plug in some obvious numbers, there should be a lot of vacuum energy – an amount that is much, much, *much* to large to account for the dark energy. We have to assume that the vacuum energy is almost, but not exactly, irrelevant to the cosmic expansion. On the other hand, cosmologists believe that, immediately after the Big Bang, the universe experienced a short period of superfast expansion called "cosmic inflation." Vacuum energy could well account for this.

Questions to consider:

1. As we saw in Lecture 5, a stretched wire can vibrate in standing wave patterns at many different frequencies. Explain why such a wire can never be absolutely still, even at its minimum possible energy.
2. In some highly speculative cosmological theories, the entire visible universe had its origin as a quantum "fluctuation" in a primordial quantum vacuum. Does this really count as "making the universe out of nothing?" (Does a quantum vacuum really count as "nothing?")

Quantum Cloning, Lecture 19

With this lecture we're starting Section 4 of our course, in which we will explore a contemporary topic in quantum mechanics research: quantum information and quantum computing-my own field of research speciality.… Our question is how can we use quantum systems to store, retrieve, transmit, and process data?

We can use single photons, atoms, and electrons to perform our tasks. In this part of the course, we will think about and understand the limitations imposed by quantum physics as well as the opportunities it affords. This is not really a question about futuristic technology. It is mostly a deep question about nature. Rolf Landauer said, "Information is physical." All information is related to physical states and physical processes of physical systems. We will consider what quantum physics can tell us about the basic concept of information.

Classical and quantum information are alike in many ways. Classical information is the type of information that can be stored in classical (macroscopic) systems. This is the sort of information that we are familiar with in everyday life. It can be changed from one physical form to another. If we consider just eh classical information generated by and corresponding to this lecture, we see the diverse range of forms it can take. For this lecture, classical information includes light and sound in the studio, electrical signals in the camera, magnetic patterns on a videotape, tiny dimples on a DVD, reflected laser light in a DVD player, more electrical signals, and finally light and sound again. Yet the information remains the same throughout.

The basic unit of classical information is the "bit." A bit is a binary digit, which can be either 0 or 1. This can stand for "yes" or "no, "on" or "off," etc. We can use different physical systems to represent bits, and any sort of information can be encoded into a series of bits. We can use bits to measure "how much information" something contains. How many bits do we need to store a novel? A nice photograph? A minute of music on my digital player? All of these have an information content of about 1 megabyte (8 million bits).

On the other hand, quantum information is the type of information that can be stored in quantum systems. Like classical information, we can transform the physical form of quantum information. The basic unit of quantum information is the "qubit." A qubit is a quantum system with just 2 basis states: (We have seen a couple of examples already: a single photon in an interferometer and a spin-½ particle.) We can call the basis states $|0\rangle$ and $|1\rangle$. In addition to the basis states, a qubit may be in any superposition state $a|0\rangle + b|1\rangle$. If we have more than 1 qubit, they can be entangled with each other. Qubits have lots of possibilities!

Qubits can be used to send classical information, if we wish. For example, Alice wishes to send Bob a 1bit message (0 or 1). She prepares a spin-½ particle in the state $|\uparrow\rangle$ for 0, $|\downarrow\rangle$ for 1. The spin is sent to Bob, who makes a z measurement and reads the message. But there are more spin states available. Can Alice send more than 1 bit in a single qubit? Suppose she wants to send a

1bit message. She encodes 00 by $|\uparrow\rangle$, 01 by $|\downarrow\rangle$, 10 by $|\rightarrow\rangle$ and 11 by $|\leftarrow\rangle$. All of these available states of a single spin. This message will not get through, because Bob cannot read it. He can correctly tell $|\uparrow\rangle$ from $|\downarrow\rangle$ using z, or $|\rightarrow\rangle$ from $|\leftarrow\rangle$ using x, but no measurement will let him distinguish all 4 spin states. The capacity of a qubit for sending classical information is 1 bit.

It is not so straight forward to send qubits via bits. This depends on exact definitions. A worst, it is impossible. At best, it will take very many bits to describe the exact superposition state $a|0\rangle + b|1\rangle$ of a single qubit.

The fundamental difference between classical and quantum information is that, while quantum information cannot be exactly copied, we can always in principle copy classical information. In classical physics, observing a system need have no effect on it. By carefully measuring our bits, we can duplicate them exactly. The ability to copy classical information is a huge problem of copyright law, intellectual property, and privacy!

To consider how we would copy, or try to copy, quantum information, we imagine a "quantum cloning machine" that would take as input a single qubit and produce as output 2 qubits with exactly the original state: $|state\rangle \Rightarrow |state\ state\rangle$. Imagine that the cloning machine works for the states $|\uparrow\rangle$ and $|\downarrow\rangle$ of a spin-½ particle. That is, $|\uparrow\rangle \Rightarrow |\uparrow\uparrow\rangle$ and $|\downarrow\rangle \Rightarrow |\downarrow\downarrow\rangle$. For simplicity, assume there are no measurements, so that only update rule I applies. How does the cloning machine work for $|\rightarrow\rangle = s|\uparrow\rangle + s|\downarrow\rangle$?

$$|\rightarrow\rangle = s|\uparrow\rangle + s|\downarrow\rangle \Rightarrow s|\uparrow\uparrow\rangle + s|\downarrow\downarrow\rangle$$

But the result is an entangled state of 2 spins, not the product state $|\rightarrow\rightarrow\rangle$ we wished for. The quantum cloning machine therefore has to fail for some input states!

In 1982, the "quantum no-cloning theorem" was proved in this way by William Wootters and Wojciech Zurek, and in a different way by Dennis Dieks. A perfect quantum cloning machine is impossible. Quantum information cannot be exactly copied.

We now move on to the science fiction story to illustrate the fact that if we *did* have a perfect cloning machine, then we could send 2 bits in 1 qubit. In our story, Alice sends Bob the 4 states $|\uparrow\rangle$, $|\downarrow\rangle$, $|\rightarrow\rangle$, $|\leftarrow\rangle$ as before. Bob uses a cloning machine to make 2000 copies. He now has: $|\uparrow\uparrow\uparrow\ldots\rangle$, $|\downarrow\downarrow\downarrow\ldots\rangle$ $|\rightarrow\rightarrow\rightarrow\ldots\rangle$, $|\leftarrow\leftarrow\leftarrow\ldots\rangle$.

Bob measures z on the first 1000 spins.

If he has $|\uparrow\uparrow\uparrow\ldots\rangle$, he will obtain +½ all 1000 times.

If he has $|\downarrow\downarrow\downarrow\ldots\rangle$, he will obtain –½ all 1000 times.

If he has $|\rightarrow\rightarrow\rightarrow\ldots\rangle$ or $|\leftarrow\leftarrow\leftarrow\ldots\rangle$, he will obtain +½ and –½ about 500 times each. Bob also measures x on the next 1000 spins. Combining his results, Bob can determine which of the 4 original states Alice sent and read her 2bit message.

Why can a qubit only convey 1 bit of classical information? Part of the answer lies in the quantum no-cloning theorem.

Questions to consider:

1. Write a paragraph that clearly explains to your Aunt Mary the essential difference between bits and qubits. (If your own Aunt Mary happens to be a quantum physicist, pick some one else's Aunt Mary.)
2. Think of some technical and legal methods by which we try to make it hard to copy certain kinds of classical information. (This is done for privacy, copyright, and other reasons.) Are any of them foolproof?

Quantum Cryptography, Lecture 20

Now, this time, we're going to see how quantum information and the no-cloning theorem play out in action. We're going to see how the laws of quantum physics will help us to keep secrets. We're going to talk about the subject of quantum cryptography. So, let's begin.

The science of cryptography is about keeping certain information private. To think about cryptography, we begin with an example involving Alice and Bob, two characters we met in our last lecture (and whose names also appear frequently in examples in journals of mathematical cryptography). In our example here, Alice wishes to send a message to Bob that cannot be read by any eavesdropper, whom we'll call Eve. They do this by agreeing on a secret code for their messages. Many codes can be "broken" by cryptanalysis. However, there is a type of secret code that cannot be broken, called a "1time pad." A 1time pad uses secret "key" information to encode the message. If Eve lacks the key, she cannot read the message. We can describe the 1time pad using strings of bits. There is a "plaintext string," a "key string," and a "ciphertext string." If Eve intercepts the ciphertext but lacks the key, she cannot read it. Bob, with the key, can decrypt the message and read the plaintext.

The big problem with this involves key distribution. If Alice and Bob use the same key over and over, it becomes insecure, and a clever Eve can begin to read their messages. They must only use the key once! (This is why it is called a 1time pad.) How can Alice send Bob a new key without Eve reading it? Alice might send the key in a tamper-proof box. Bob could check it for Eve's fingerprints, etc. But Eve might be able to make a copy of the key without leaving any traces, so that Alice and Bob would be fooled and thinking their key is still secret. No classical method of key distribution can be 100% save for Eve.

In 1984, Charles Bennett and Gilles Brassard showed how to use quantum mechanics to solve the problem of key distribution. Their idea, known as "BB84," marks the birth of "quantum cryptography." We still use another example, with our stock characters, to describe the BB84 method.

In our example, Alice sends to Bob a series of spins, their states chosen randomly from the set $|\uparrow\rangle$, $|\downarrow\rangle$, $|\rightarrow\rangle$, $|\leftarrow\rangle$. Bob measures each spin, randomly choosing z or x for each. Then Alice and Bob talk on the phone. (Eve may be listening.) They do not say which states were sent, but they do discuss the measurements Bob made. Alice tells him which spins were measured using the "right" axis. They use the good ones for their secret key and throw out the others.

In our example, why can't Eve intervene and learn the secret key? She cannot do so because she cannot simply make exact copies of the spins as they go from Alice to Bob. The no-cloning theorem prevents this. If she makes measurements on the spins, she is bound to choose the "wrong" axis a lot of the time. This will necessarily introduce errors at Bob's end. If Alice and Bob compare a few hundred of their key bits over the phone, they can detect this. Eve must have quantum fingerprints." BB84 works because of complementary of x and z, plus the no-cloning theorem.

Questions to consider:

1. To use BB84 scheme, Alice and Bob must individually generate some random sequences of zeros and 1s. Otherwise, if Eve can guess what sequences they are using, she can also guess their key. Make some suggestions for generating these random bits. (Extra points for using quantum physics to do it!)
2. Imagine that Eve possesses a quantum cloning machine that can perfectly duplicate qubit states. How can she use this magical device to "break" the BB84 quantum key distribution?

Bits, Quibits, and Ebits, Lecture 21

Every age in history has a basic metaphor… a way of organizing our thinking about the world around us.… And today…we sort of inevitably think of the world as a huge network, a vast system of information exchange.… What we want to do is we want to discover the fundamental rules of that information network.… All of this is based on something called "information theory."

"Information theory" is the mathematical theory of communication and related subjects, invented by Claude Shannon in 1948. The concepts of information theory include bits, codes errors, and so on. The study has been vital to the development of telecommunications, computing, and many other fields. Information theory is all about information "resources" and information "tasks." In focuses on which resources are required to perform a given task. These resources may include time, storage space, power, etc. Tasks may include storage of data, overcoming noise, and keeping a message private.

Shannon's information theory does not take quantum mechanics into account. A "quantum information theory" would include quantum resources and tasks. We can identify 3 types of quantum resources: bits (Alice sends 1 bit of classical data to Bob), qubits (Alice sends 1 qubit of quantum data to Bob), and ebits (Alice and Bob share an entangled pair of qubits – like 2 spins in a total spin 0 state – which amounts to "1 bit of entanglement".) Bits and qubits are "directed resources" (Alice to Bob or Bob to Alice), but ebits are "undirected." Together we will work to answer the question of how these different resources are related to each other.

Charles Bennett put together some simple principles about quantum information resources. We'll call these "Bennett's laws." Each law is of the form $X \geq Y$, which is read, "X can do the job of Y." this means that the resources labeled X can perform the same task as the resources labeled Y.

Bennett's first law says that 1 qubit ≥ 1 bit. We have already seen this in our example in which Alice can use a qubit to send a 1 bit message to Bob. However, notice that 1 qubit ≱ 2 bits because Alice cannot transmit 2 bits in 1 qubit.

Bennett's second law is that 1 qubit ≥ 1 ebit. This is also easy to understand. Alice can make a pair of spins in a total spin 0 state, then send 1 of the 2 entangled qubits to Bob. Qubits are the most capable of the 3 resources. We can use them for anything. We cannot send messages using only an ebit. This is because entanglement by itself cannot be used to send either classical or quantum messages, although it can assist in sending messages.

Bennett's third law says that 1 ebit + 1 qubit ≥ 2bits. This was discovered by Bennett and Stephen Wiesner in 1992 and is sometimes called "dense coding." We return to Alice and Bob to consider this law. Alice and Bob initially share an ebit (say, 2 spins in a total spin 0 state). Alice makes 1 of 4 possible rotations on her spin. These are either no rotation or a 180° rotation about the x, y, or z axes. Her choice of rotation represents a 2bit message: 00, 01, 10, or 11. Alice sends her qubit to Bob. Bob now makes a special measurement called the "Bell measurement" on the pair of qubits. From this, he is able to deduce which rotation Alice made – and thus he can read the 2bit message.

Dense coding appears to be very strange, because it seems that the 2 bits are carried by 1 qubit. However, there are 2 qubits involved, though 1 of them stays in Bob's possession the whole time. If we make a diagram of the process, it appears that some information has traveled "backward in time"!

Bennett's forth law says that 1 ebit + 2 bits ≥ 1 qubit. Here is how this law plays out in another Alice-and-Bob example. The two initially share an ebit. In addition, Alice has a qubit that she'd like to transfer to Bob. Alice makes a Bell measurement on the 2 qubits she has. She sends the result to Bob as a 2bit classical message. Bob can use this information to choose a rotation for his qubit (either no rotation or a 180° rotation about he x, y, or z axis).

Afterward, his qubit is in exactly the same state as Alice's original was! This process, discovered in 1993 by Bennett and several co-workers, is called quantum teleportation.

It is important to note here that teleportation is about information transfer, not transportation. It is barely possible to do teleportation of 1 qubit in the lab. Teleporting the quantum information in a human being is at least 10^{27} times harder – and we would need a lot of entangled matter. Because of the no-cloning theorem, the original qubit is necessarily wiped out. Suppose Alice can send qubits to Bob only occasionally, but she can send classical bit at any time. They may store up ebits when quantum communication is possible, then send their qubits when ever they like using teleportation.

How much are different resources worth? If classical bits cost nothing, then qubits and ebits are worth an equal amount. We turn one resource into the other for free. If ebits cost nothing (an odd assumption), then the value of a qubit is exactly 2 bits.

Questions to consider:

1. It is impossible to send more than 1 bit of classical information using just 1 qubit. Why doesn't Bennett and Wiesner's dense coding disprove this rule?

2. Suppose we consider a situation with 2 protagonists: Alice, Bob and Charles. At the onset, Alice and Bob share 1 ebit, as do Bob and Charles, but Alice and Charles do not share any entanglement. If the 3 can send only classical bits to each other, how can Alice and Charles end up with a shared ebit? Can this be done even if Charles is unable to communicate at all? (It is interesting to try to work out some basic ruses of 3-party quantum information theory.)

Quantum Computers, Lecture 22

Our everyday language struggles to cope with the nature of quantum information. [In] this lecture we're going to explore the full power of quantum information.… We will imagine a quantum computer, and we'll see what we can do with it.

Is quantum computing the future of computers? According to Moore's law, computer power is increasing exponentially over time. Roughly speaking, computer capabilities double every 2 years. Basic units of computers are growing smaller at about the same rate. They operate faster, using less energy. If Moore's law continues to hold, in a couple of decades we will be trying to use individual quantum particles for basic computer components. We will need to design quantum computers.

In a quantum computer, the memory elements are qubits. These can be in superposition states (not just $|0\rangle$ and $|1\rangle$), and huge numbers of qubits may be entangled together. While performing computations, a quantum computer operates without any measurements of any kind, even inadvertent ones. Its state therefore changes according to update rule I. (At the end of the computation, of course, we must make a measurement to read the output.) A quantum computer cannot merely do ordinary computations faster or with smaller components. It can do computations in fundamentally new ways, completely unlike any classical computer.

A quantum computer could solve some mathematical problems much more efficiently than a classical computer. In 1992, Richard Jozsa and David Deutsh proposed the Deutsch-Jozsa problem, which first showed that quantum computers could be more powerful than classical ones. The computer can evaluate a function $f(n)$, where n ranges from 1 to N. The value of the function is always either 0 or 1. We happen to know that the function is either constant (always 0 or always 1) or balanced (0 or 1 equally often). How many times must we evaluate f to determine which one it is? On a classical computer, we might have to evaluate f more than N/2 times to be certain. If the function is really hard to compute, this might take a while.

However, on a quantum computer, we can answer the question by evaluating f only once, on a superposition of all possible inputs.

In 1996, Lov Grover showed that a quantum computer could help solve the "inverse phonebook problem." A phone book is an alphabetical list of names together with phone numbers. But suppose we only have the phone number and want to find the name. How many names do we have to look up to find it? Suppose there are 1 million entries. A classical computer would have to look up about 500,000 names on average, and 999,999 names in the worst-case scenario. A quantum computer could do the same job by consulting the phone book only 1000 times, each time looking up a superposition of all the names.

The most exciting application is "quantum factoring," discovered by Peter Shor in 1994. In this application, we are given a very large number, perhaps with hundreds of digits. This number Is the product of 2 smaller numbers. Can we find the factors? On a classical computer, this is a very hard problem. A 200-digit number was recently factored by hundreds of computers working together for over a year. A 500-digit number is so much harder that no imaginable computer could ever do the job. Shor proved that a quantum computer could factor integers very efficiently. A 500-digit number is only about 16 times harder than a 200-digit one. Because much modern cryptography is based on factoring, if someone invents a quantum computer, a lot of secret data will no longer be secret!

Can a quantum computer actually be built? Many scientist are working very hard to build one. Design ideas include atoms suspended in laser beams, nuclear spins in magnetic fields, superconducting loops near absolute zero, and single electrons in semiconductors. Even the best efforts so far involve just a few qubits working for a few seconds.

The would-be builder of a quantum computer faces a fundamental dilemma. On the one hand, the computer must be extremely well isolated from the outside. Otherwise, stray molecules and photons would make inadvertent measurements of the computer's state, interrupting the magic of update rule I. On the other hand, the different parts of the computer must interact extremely rapidly with each other, so that the computation can be done. The good news is that we need not be perfect. By using "quantum error correction," the computer can tolerate a little outside interference. However, the bad news is that nobody knows how to resolve the fundamental dilemma.

In the mid-19th century, Charles Babbage designed mechanical equivalents of modern computers. His computing ideas were never put into real practice until the development of electronics. Our present ideas about how to do quantum computing may the modern equivalent of Babbage's gears and wheels.

Questions to consider:

1. Your lecturer has a bet with a colleague about whether or not quantum computers will become practical within 20 years. Which way would you bet?

2. Suppose a working quantum computer became available tomorrow. What would be it's main practical impact?

3. We said that the builder of a quantum computer faces a fundamental dilemma. Why does this same dilemma not apply to an ordinary "classical" computer?

Many world or One?
Lecture 23

In the final 2 lectures of this course we will probe some philosophical issues about quantum mechanics. We'll ask: What does quantum mechanics mean? What does it tell us about the nature of reality?… In this lecture we're going to examine three different ways that physicists have come to interpret the meaning of quantum mechanics.

Even though quantum mechanics is more than 80 years old (and some parts more than 100), there is still a lot of debate about its interpretation. Physicists agree on how to use quantum mechanics. The question is what the theory is telling us about the nature of reality. Some issues are philosophical: Is the world really nondeterministic? Is a quantum state objective – something "out there" or "all in our heads"?

One key issue is the question of measurement. Measurement seems special. It forces us to use the probabilistic and instantaneous update rule II rather than the smooth and predictable update rule I. Yet any measurement apparatus is made of atoms. Why can we not treat it as just another quantum system?

There have been 3 main schools of interpretation: the Copenhagen interpretation, the hidden-variables interpretation, and the many-worlds interpretation. The Copenhagen interpretation is the standard approach. Championed by Bohr, this interpretation rests on the principle of complementarity. This interpretation says that the microscopic world does not really "exist" on it's own, independent of an observer. You can sum up the idea here in this way: "No phenomenon is phenomenon until it is an observed phenomenon." In this interpretation, measurement is special because it is the process by which quantum things are amplified into macroscopic reality.

The line between "microscopic" and "macroscopic" may be drawn in various places. We can analyze at least some of the workings of a measurement apparatus in a quantum-mechanical way. In the thought experiment of Schrödinger's cat, the cat is seemingly brought into a superposition state $a|\text{alive}\rangle + b|\text{dead}\rangle$. Eugene Wigner imagined his friend examining Schrödinger's cat. Does Wigner's friend now exist in a superposition state?

The Copenhagen interpretation has it's Drawbacks. It is not clear, for example, that orthodox approaches to quantum theory will be good enough for challenges like quantum gravity or quantum cosmology.

The hidden-variables interpretation is somewhat less popular. It was discussed most deeply by David Bohm, beginning in 1952. The work was based an earlier idea of de Broglie, who thought that both the quantum wave and the quantum particle exist together. The wave acts to "pilot" the particle through space. Bohm was able to create a theory that would appear exactly like quantum mechanics in any experiment, but the particles always had definite positions and velocities at every given moment, and they moved in a complicated but deterministic way.

What about Bell and entanglement? Bell's argument means that Bohm's hidden-variable theory must work in a non-local way. That is, distant parts of the universe can instantaneously affect each other. Bohm did not regard this as a flaw. He saw this as an expression of a large-scale cosmological order, something quite different from the "reductionist" ideas common to modern science. Relatively few quantum physicists subscribe to Bohm's ideas, though they continue to be discussed and developed.

The many-worlds interpretation was proposed by Hugh Everett III in 1957. The basic idea is that the measurement apparatus and observers are all quantum systems and that the whole universe always evolved according to update rule I. The quantum state thus evolves deterministically. The apparent randomness in quantum mechanics arises because we can see part of the whole.

The many-worlds interpretation gives a strange account of measurement. Consider a simple universe containing an observer Joe and a spin-½ particle. The spin starts out in the state $a|\uparrow\rangle + b|\downarrow\rangle$, and Joe starts out in the state $|\text{Joe}_0\rangle$.

The initial state of the universe is

$$a|\text{Joe}_0,\uparrow\rangle + b|\text{Joe}_0,\downarrow\rangle$$

Joe now measures z on the spin. This is an interaction (update rule I) that works like this on basis states:

$|\text{Joe}_0, \uparrow\rangle \Rightarrow |\text{Joe sees ``up,''}\uparrow\rangle$
and
$|\text{Joe}_0, \downarrow\rangle \Rightarrow |\text{Joe sees ``down,''} \downarrow\rangle$

The new state of the universe is

$$a|\text{Joe sees ``up,''} \uparrow\rangle + b|\text{Joe sees ``down,''} \downarrow\rangle$$

In each branch of this superposition, Joe sees only 1 thing, and what Joe sees agrees with the state of the spin. But both branches are still present in the overall state of the universe. It is as if the world has split in 2, each branch invisible to the other. In the process of measurement, the observer becomes entangled with the observed.

The many-worlds interpretation is controversial but increasingly popular. One positive aspect of this interpretation is that it gets rid of any special measurement process and lets us apply quantum theory to the entire universe. This makes it attractive for physicists trying to develop a "theory of everything." However, it does have problems. One key one is that it asserts the existence of vast numbers of unobservable branches other than what we see, which seems to violate the logical principle of Occam's Razor. It involves another difficult puzzle as well: In our example, why does Joe see "up" with probability $|a|^2$ and "down" with probability $|b|^2$? Both branches are present, but why does he seem to experience them with this likelihood? The universe of the many-worlds interpretation contains all quantum possibilities in a vast, ever-more-complicated, stupendously entangled quantum superposition.

Questions to consider:

1. What do you find least satisfactory about each of the 3 main interpretations of quantum theory described in this lecture?

2. The principle of Occam's Razor has been invoked both to criticize the many-worlds interpretation (why imagine so many other worlds)? And to defend it (why imagine that the principle of superposition has any limits?). Which argument seems more sensible to you and why?

3. Try to imagine how Bohr and Einstein might have responded to the many-worlds interpretation of quantum mechanics. Write a short fictional dialogue between them, discussing the idea.

The Great Smoky Dragon, Lecture 24

The quantum realm is a wonderfully strange place. Indeed, we are not entirely sure just what kind of place it is. There is significant disagreement about the meaning of quantum mechanics…. In this final lecture, I would like to reflect on what it is that makes quantum mechanics so strange and so mysterious.

We return to our example of the photon in the Mach-Zehnder interferometer. In this example, interference challenges our intuition. Block either beam, and either detector might register the photon. Leave both beams open, and only 1 detector can possibly register it. Interference can occur when no measurement is made of which path the photon travels. This leads us to an astonishing point: When interference occurs, no physical record is made *anywhere in the universe* of the path of the photon. The photon on it's journey is "informationally isolated" from the rest of the universe. Remember, "Quantum mechanics is what happens when no one is looking."

The "magic" of quantum mechanics is like a strange magician's trick box. With the box, we believe that we could peer inside and find out how the trick works. With the quantum mechanics box, the trick only works when the box is absolutely closed. We cannot find out how it works, even in principle.

Our description of the magic in the box is quantum mechanics, which is full of strange mathematical abstractions: states, amplitudes, etc. We can use quantum mechanics to perform amazing tricks, but the magic box remains no less mysterious.

Why is it hard to observe quantum interference of a baseball? Large objects are extremely difficult to isolate from the outside world. To observe baseball interference, we would have to remove all photons and gas molecules, then cool he baseball fantastically close to absolute zero. We would even have to worry about how the baseball's gravity is affecting nearby atoms! The point here is that macroscopic atoms are very strongly connected to the rest of the world. If we are very careful, we can observe interference for photons, electrons, atoms, etc. But we cannot cut a baseball away from the rest of the world and close the lid of the magic box.

Quantum mechanics is sometimes called the "Great Smoky Dragon." John Wheeler introduced a cartoon to illustrate the nature of quantum mechanics. The dragon's tail appears in the start of the experiment. The dragon's head bites one of the particle detectors at the end. In between, the dragon is shrouded in smoke, and we can never say exactly what its shape is.

The Great Smoky Dragon is a metaphor for the elusiveness of the quantum realm. It is found in every part of quantum mechanics, shrouded by the uncertainty principle and shielded by the principle of complementarity. It has a delicate touch; it can tickle a hair-trigger bomb without setting it off. A pair of identical particles is less like 2 dragons than a single dragon with 2 tails and 2 heads. Feynman's ribbon trick gives us a hint of how the dragon twists among particles with spin. In Feynman's view, the dragon gets from here to there by wriggling through everywhere in between. Virtual dragons stretch invisibly from particle to particle, carrying forces between them. Even when space appears empty, it fluctuates with the stirrings of the dragon. Quantum information reminds us of the Great Smoky Dragon, for it cannot be pinned down and copied. We can use the hidden-ness of the dragon for our own purposes, sending secret messages that no eavesdropper can penetrate. Dragons carry signals in strange ways, even snaking backward in time; and with a quantum computer, we can quickly solve hard mathematical problems entirely inside the cloud of smoke.

Entanglement is the most dragonish aspect of quantum mechanics. If 2 particles are in an entangled state together, then neither of them can be entangled with any other particles in the universe. The relationship of entanglement is entirely "private." This fact is called the monogamy of quantum entanglement. (Abner Shimony called entanglement "passion at a distance.")

How should we regard the Great Smoky Dragon? It is a Copenhagen picture. The tail and head are where the dragon emerges into the macroscopic world; the smoky in-between is the indescribable quantum realm. (John Wheeler was a student of Niels Bohr.)

Other interpretations deal with the dragon in different ways. The hidden-variables interpretation asserts that the dragon has a definite shape. This shape is strange because parts of the world that seem far apart are actually close together on the dragon.

According to the many-worlds interpretation, the dragon has no tail and no head. Everything is inside the smoke, including us! When we thing we see a tail or a head, we are only seeing a tiny part of the whole dragon. Which encompasses every possible world.

Non of this makes the Great Smoky Dragon less mysterious. Though its actions shape everything we see in the world, elusiveness is the quantum dragon's most essential feature.

Questions to consider:

1. In his writings on complementarity, Bohr laid great stress on "amplification"-the process by which a quantum event is magnified into a macroscopic measurement result. Based on the ideas in this lecture, explain how this takes the effect across the boundary between the quantum and classical realms.

2. Think about what you have learned about quantum mechanics from the previous lectures and pick out the phenomenon that you find most strange or striking. How does Wheeler's metaphor of the Great Smoky Dragon illuminate quantum physics in this example?

Timeline

5th century BC: Democritus proposes that all matter is composed of tiny, indivisible atoms.

4th century BC: Aristotle develops a sophisticated theory of physics in which matter is continuous and infinitely divisible.

1678: Christiaan Huygens writes his *Treatise on Light*, exploring the Wave theory. (The book is eventually published in 1690.)

1687: Isaac Newton publishes his *Principia Mathematica Naturalis Philosopiae (Mathematical Principles of Natural Philosophy)*, establishing the basic laws of classical mechanics.

1704: Isaac Newton publishes his *Opticks*, exploring the corpuscular theory of light.

1803: John Dalton proposes the laws of chemical combination can be explained by assuming each element is made of its own type of atom; Thomas Young publishes the results of his 2-slit experiment, establishing the wave character of light and measuring its wavelength.

1862: James Clerk Maxwell shows that light is an electromagnetic wave, a traveling disturbance in electric and magnetic fields.

1866: Maxwell develops the "kinetic theory" of gases based on the idea that gases are composed of huge numbers of tiny molecules; a decade later, Ludwig Bolzmann independently duplicates Maxwell's work and considerably extends the theory.

1887: The photoelectric effect is discovered by Heinrich Hertz.

1900: William Thomson, Lord Kelvin, delivers a lecture at Royal Institution nothing "two dark clouds" over the classical theory of heat and radiation: the Michelson-Morley experiment and blackbody radiation; Max Planck introduces the quantum hypothesis to explain the properties of blackbody radiation.

1905: Albert Einstein elaborates the quantum hypothesis and explains the photoelectric effect.

1907: Einstein applies the quantum hypothesis to the vibration of atoms in a solid, explaining the anomalously low heat capacity of some materials.

1911: Ernest Rutherford shows that the atom consists of a massive Central nucleus surrounded by orbiting electrons; discovery of superconductivity.

1913: Niels Bohr publishes his quantum theory of atomic structure.

1922: Otto Stern and Walter Gerlach do the first experiment showing that Atomic spins can only have discrete values.

1924: Louis de Broglie proposes, in his doctoral thesis, that wave-particle duality applies to matter as well as to light (a few years later, this was confirmed in diffraction experiments with electrons); Satyendra Bose develops the quantum statistical theory of photons, which Einstein later extends to other particles ("bosons"); Wolfgang Pauli proposes the exclusion principle for electrons in an atom.

1925: Werner Heisenberg develops his version of quantum mechanics, sometimes called "matrix mechanics."

1926: Erwin Schrödinger develops his version of quantum mechanics, called "wave mechanics," based on de Broglie's matter waves (this is later shown to be exactly equivalent to Heisenberg's matrix mechanics); Max Born proposes his rule for interpreting Schrödinger's waves as probability amplitudes; Enrico Fermi and Paul Dirac develop the quantum statistical theory of particles that obey the exclusion principle ("fermions").

1927: Heisenberg proposes the uncertainty principle; Bohr proposes the principle of complementarity, the basis for the Copenhagen interpretation; the Bohr-Einstein debate begins with vigorous discussions at the Fifth Solvay Conference on Physics in Belgium.

1930: The Bohr-Einstein debate ends its first phase during further vigorous discussion at the Sixth Solvay Conference on Physics; after this date, Einstein no longer argues that quantum mechanics is inconsistent, but he still believes it to be incomplete.

1935: Einstein, Boris Dodolsky, and Nathan Rosen draw attention to quantum entanglement (a term coined by Schrödinger in the same year) and argue that quantum mechanics must be incomplete; Bohr responds, but the question remains unresolved.

1937: Discovery of superfluidity in He II.

1942: Richard Feynman, in his doctoral thesis, proposes the "sum-over-histories" approach to quantum mechanics.

1948: Feynman applies the "sum-over-histories" idea to quantum electrodynamics, introducing Feynman diagrams; Hendric Casimir shows that 2 metal plates must attract one another due to their effect on the quantum vacuum; Claude Shannon develops (classical) information theory.

1952: David Bohm proposes the hidden-variables interpretation of quantum mechanics.

1957: Hugh Everett III proposes the many-worlds interpretation of quantum mechanics.

1960: Invention of the laser.

1964: John Bell proves that no local hidden-variable theory can account for quantum entanglement.

1978: John Wheeler proposes his delayed-choice experiment.

1982: The quantum no-cloning theorem is proved by William Wootters and Wojciech Zurek and independently by Dennis Dieks.

1984: Charles Bennett and Gilles Brassard propose quantum key distribution, the beginning of quantum cryptography.

1992: Bennett and Stephen Wiesner invent dense coding, in which 1 ebit and 1 qubit can be used to transmit 2 classical bits of information; David Deutsch and Richard Jozsa show that a quantum computer could solve a particular mathematical problem much faster than any classical computer.

1993: A collaboration of quantum physicists (including Bennett, Briassard, Josza, and Wootters) invents quantum teleportation, in which 1 ebit and 2 classical bits can be used to transmit a qubit; Avshalom Elitzur and Lev Vaidman devise the bomb-testing thought experiment.

1994: Peter Shor shows that quantum computer could factor a large integer much faster than any classical computer.

1995: First Bose-Einstein condensate is created in the laboratory.

1996: Lov Grover shows that a quantum computer could solve the inverse phonebook problem faster than any classical computer.

1998: The expansion of the cosmos is discovered to be accelerating due to an unknown "dark energy," possibly related to quantum vacuum energy.

Glossary

absorption: A process in which a photon deposits its energy in matter and is destroyed.

amplitudes: The numerical coefficients in a superposition. If the amplitude is a, then the probability of finding that result in a measurement is $|a|^2$.

angular momentum: A measure of how much rotational motion is present in a system, analogous to momentum.

antiparticles: Particles that have the same mass but otherwise opposite properties to "ordinary" particles. Every type of particle has an antiparticle (although photons are their own antiparticles).

antisymmetric: The mathematical property of the quantum state of fermions, which pick up a negative sign when 2 identical particles are swapped.

atom: To Greek philosophers, a tiny and indivisible particle out of which all matter is made. In modern usage, atoms are the basic constituents of chemical elements, but they are in turn made up of smaller particles, including protons, neutrons, and electrons.

basis: A set of quantum states corresponding to the various possible outcomes of a measurement on a quantum system. Since there are many possible complementary measurements, there are many possible basis sets for that system.

beam splitter: *See* **half-silvered mirror**.

Bell's inequality: A mathematical relation that holds true in any local hidden variable theory but may be violated in quantum mechanics.

bit: The basic unit of classical information, defined as the information carried by a single binary digit (0 or 1).

blackbody radiation: The electromagnetic radiation emitted by a hot, absorbing object called a "blackbody." All blackbodies at a given temperature emit radiation with the same characteristics.

Bohr model: The atomic model proposed by Niels Bohr in 1913 in which electrons can only move in discrete orbits around the nucleus. When light is absorbed or emitted, the electron "jumps" from one orbit to another.

Born rule: The rule introduced by Max Born to interpret quantum waves. The intensity of the wave, which is the square of the absolute value of the amplitude, gives the probability of finding the particle.

Bose-Einstein condensate: A low-density cloud of atoms extremely close to absolute zero, so that all of the atoms are found in the same quantum state. Though this was predicted by Einstein in the 1920s, it was not created in the lab until 1995.

bosons: Identical quantum particles such as photons, helium atoms, etc., whose states do not change when the particles are swapped. Bosons have a tendency to be in the same state.

branch: In the many-worlds interpretation, one part of the superposition state of the whole universe – in effect, one "world."

Casimir effect: The weak attraction between metal plates, predicted by Hendrik Casimir in 1948 and later observed in he lab. The force is due to the plates' effect on the quantum vacuum.

ciphertext: In cryptography, the representation of the message that is actually transmitted. Generally, an eavesdropper only ahs access to the cyphertext and wishes to determine the plaintext. *See also* **key**.

classical information: The familiar type of information contained in text, audio, video, or data messages, measured in bits and described by Shannon's information theory.

classical mechanics: The theory of mechanics based on Newton's laws of motion.

classical physics: A general term that includes classical mechanics, thermodynamics, and electromagnetism. Classical physics prevailed before 1900.

code: Any way of representing information. Specifically, a code is an association of a particular message with a particular representation – representing "no" with "0," for example. In cryptography, a code may be used to conceal the meaning of the message.

coherent light: Light of a single wavelength and direction.

complementarity: The principle that different observations are incompatible. Thus we cannot design an experiment that measures both a particle's position and its momentum. Complementary quantities cannot both have exact values at the same time.

continuous: Having a whole connected range of values. The real numbers are continuous; between any 2 different real numbers there is an infinite range of intermediate values.

Cooper pairs: Bound pairs of electrons in a low-temperature metal. Although electrons themselves are fermions, Cooper pairs are bosons.

Copenhagen interpretation: The standard interpretation of quantum mechanics developed by Bohr and others, based on the principle of complimentarity. In this interpretation, we cannot ascribe a definite meaning to quantum events until a measurement is made and the result is amplified to the macroscopic realm.

cosmic inflation: A brief period of extremely rapid expansion early in the history of the universe, like driven by quantum vacuum energy.

cryptanalysis: The effort to "break" a secret code by mathematical analysis.

cryptography: The science of maintaining the privacy and integrity of information.

dark energy: A kind of unseen energy, nature unknown, that drives the acceleration expansion of the universe. One theory is that dark energy is the energy of the quantum vacuum.

de Broglie wave: A wave associated with a particle such as an electron, in accordance with the proposal of Louis de Brogie.

delayed-choice experiment: A thought experiment proposed by John Wheeler in which the decision between complementary measurements is made after the experiment is almost completed.

determinism: The belief that future events are completely determined by the present state of the universe – for example, by the exact positions and moments of all the particles in the world. In this vies, "randomness" is simply due to the practical inability to know the present and calculate the future in sufficient detail; in fact, nothing can be truly "random."

Deutsch-Jozsa problem: the problem of determining whether a binary function is "balanced" or "constant." Deutsh and Jozsa determined that a quantum computer can answer this question much faster than any ordinary computer.

diffraction: Having only disconnected values. The whole numbers are discrete because they are separated from each other; for example, here is no whole number between 2 and 3. (The opposite of continuous.)

distinguishable: Possible to tell apart, at least in principle, by some measurement. Quantum particles of different types (a proton and a neutron, say) are distinguishable. (The opposite of identical.)

eavesdropper: A person who tries to intercept private information without authorization.

ebit: The basic unit of quantum entanglement, defined as a pair of entangled qubits. As an example 2 spins in a total spin 0 state form an ebit.

electromagnetic wave: A traveling disturbance in the electromagnetic field. Light is an electromagnetic wave; other examples with other wavelengths include radio waves, infrared radiation. Ultraviolet radiation, X-rays, and gamma rays.

electromagnetism: The branch of physics that deals with the behavior of electric and magnetic fields.

electron: A low-mass, negatively charged particle that orbits the nucleus of an atom.

Elitzur-Vaidman bomb-testing problem: A thought experiment proposed by Avshalom Elitzur and Lev Vaidman in 1993, showing the surprising features of quantum interference.

entanglement: The correlation of 2 distinct quantum systems. Einstein drew attention to the strange features of entanglement, and Bell used those properties to prove that quantum mechanics is inconsistent with local hidden variable theories.

EPR argument: The argument made by Einstein, Podolsky, and Rosen in 1935 that the properties of quantum entanglement imply quantum mechanics must be an incomplete description of nature. The EPR argument is based on a "criterion of reality" that was later criticized by Bohr.

excited state: A state of a quantum system, such as an atom, that has a greater energy than the ground state.

exclusion principle: The physical principle, first discovered by Pauli for electrons, that no 2 identical fermions can bi in exactly the same quantum state.

fermions: Identical quantum particles such as electrons, protons, etc., whose state acquires a negative sign when the particles are swapped. Fermions obey the exclusion principle, so that no 2 identical fermions can be in the same state.

Feynman diagram: A cartoonlike representation of a process in QED involving electrons and photons. (More general diagrams arise in more general particle theories.)

frequency: The number of wave cycles per second that pass a fixed point in space.

ground state: The state of lowest energy of quantum system such as an atom. (The opposite of excited state.)

half-silvered mirror: A partially reflecting mirror, also knows as a beam splitter. A light beam shining on a half-silvered mirror is divided into a reflected and transmitted beam, each of which has half of the original intensity.

heat capacity: The amount of heat energy necessary to increase the temperature of a material by 1°C. The anomalously low heat capacity of some solids was first explained by Einstein.

hidden variables: The conjectured unknown factors that might underlie quantum mechanics and predetermine the outcomes of measurements. Also, the assumption that such variables exist.

hidden-variables interpretation: The alternate interpretation of quantum mechanics proposed by David Bohm. Quantum mechanics is thought to be an incomplete description of nature. There are additional, hidden variables that make nature deterministic and that function in a highly non-local way.

identical: Impossible to tell apart by any conceivable measurement. Quantum particles of the same type (2 electrons, say) are identical. (The opposite of distinguishable.)

information theory: The mathematical science of communication developed by Claude Shannon in 1948. This theory, however, did not take quantum mechanics into account.

informatinally isolated: Leaving no "footprints" behind to record what happened. A photon in an interferometer is informationally isolated, so that it is impossible to say which beam it followed. Quantum interference effects only appear in systems that are informationally isolated.

interference: The phenomenon in which 2 or more waves can reinforce each other (constructive interference) or cancel each other out (destructive interference).

interferometer: An optical apparatus in which 2 or more light beams are split, redirected, and combined by beam splitters, demonstrating interference effects.

inverse phone book problem: Given only an alphabetical phonebook, the problem of finding a name associated with a given phone number. Lov Grover showed that this could be done more efficiently on a quantum computer.

ket: A mathematical object describing a quantum state. Symbolically, the ket is written this way: $|\textit{state}\rangle$, where *"state"* is just a label designating the state.

key: In cryptography, the mathematical recipe for transforming plaintext into ciphertext and vice versa.

key distribution: In cryptography, the problem of distributing secret keys to users while keeping them secret from any eavesdropper. There is no perfect solution to this in classical cryptography.

kinetic energy: For a particle of mass m moving with velocity v, the kinetic energy is $K = \frac{1}{2}mv^2$.

laser: A device that uses stimulated emission to produce coherent light.

local hidden variable theory: A hypothetical type of theory studied by Bell. In this sort of theory, the quantum realm is assumed to be governed by hidden variables that act in a local way. Bell showed that such theories are incompatible with quantum entanglement.

locality: The assumption that what happens to a particle depends only on its own variables and its immediate circumstances, not what is happening to other particles far away.

Mach-Zehnder interferometer: A particular type of interferometer including just 2 beams. We use this as our basic thought experiment for understanding quantum mechanics.

macroscopic: A generic term for phenomena and objects at the large scale. Everything that we can directly perceive may be regarded as macroscopic.

many-worlds interpretation: The alternate interpretation of quantum mechanics proposed by Hugh Everett III. Macroscopic systems, including observers themselves, are considered to be part of the quantum system. Measurement creates entanglement between system and observer, and all measurement outcomes (all "worlds") are present in various branches of the state of the universe.

mechanics: The branch of physics that deals with force and motion.

microscopic: A generic term for phenomena and objects at the small scale. When we use this term in connection with quantum physics, we mean atomic-scale phenomena and objects (which are in fact too small to see under an ordinary microscope).

momentum: For a particle of mass m moving with velocity v, the momentum (usually denoted p) is $p = mv$.

Moore's law: An observation by Gordon Moore that computer power doubles about every 2 years. This has held true for 4 decades and counting.

neutron: A massive, uncharged particle found in the atomic nucleus.

one-time pad: A type of unbreakable secret code that only uses its key once. If an eavesdropper does not have the key, the message is perfectly secure. If the key is used more than once, however, an eavesdropper may be able to break the code.

optical pumping: In a laser, adding energy to a collection of atoms to produce a population inversion.

Pauli exclusion principle: see **exclusion principle**.

photoelectric effect: The emission of electrons from a polished metal surface that is exposed to light of a sufficiently high frequency, Einstein explained this effect using quantum ideas in 1905.

photon: A light quantum; the basic particle of light.

plaintext: In cryptography, the original message to be protected by a secret code. *See also* **key** and **ciphertext**.

Planck-de Broglie relations: Mathematical relations (involving Planck's constant h) between wave and particle properties. The particle energy E is connected to the wave frequency f by $E = hf$. The particle momentum p is connected to the wavelength λ by $p = h/\lambda$.

Planck's constant: A fundamental constant of nature, usually denoted h, with a value of 6.63×10^{-34} J·sec. The tiny value of h tells us that quantum effects are most important only at the microscopic scale and that macroscopic physics appears classical.

population inversion: A situation in a laser in which there are more excited atoms than atoms in the ground state.

positrons: The antiparticles of electrons, having the same mass but opposite electric charge. Positrons and electrons can be created or annihilated in pairs.

potential energy: A particle subject to a force has energy due to its position in space. For a simple pendulum, for instance, the potential energy is lowest at the low point of the pendulum and higher at either end of its swing. Kinetic plus potential energy will remain constant as the pendulum swings.

product state: A quantum state of a pair of particles in which each particle has its own definite quantum state. Such particles are completely independent. Not all states are product states, however. If the pair is not in a product state, it is said to have quantum entanglement.

proton: A massive, positively charged particle found in the atomic nucleus.

QED: Quantum electrodynamics, the highly precise theory of electron-photon interactions developed in the 1940s by Richard Feynman and others.

quantum cloning: A hypothetical process, impossible in the real world, by which an exact duplicate is made of the quantum state of a particle.

quantum computing: The use of quantum particles to process information.

quantum electrodynamics: *See* **QED**.

quantum factoring: A superefficient method of finding the factors of large numbers by using a quantum computer. Discovered by Peter Shor in 1994.

quantum hypothesis: Max Planck's radical idea, proposed in 1900, that a hot object only emits or absorbs light energy in discrete units, or quanta. The energy of 2 quantum of light is $E = hf$, where h is Planck's constant and f is the light frequency.

quantum information: The distinctive kind of information that is carried by quantum particles. Quantum information is measured in qubits.

quantum mechanics: The theory of mechanics developed between 1900 and 1930 that replaced classical mechanics based on Newton's laws.

quantum no-cloning theorem: The mathematical proof by Wootters, Zurek, and Dieks that it is impossible to perfectly duplicate the state of a quantum particle.

quantum physics: A general term for the physics of the microscopic world.

quantum theory: A more general term for quantum mechanics and related theories.

qubit: The basic unit of quantum information, defined as the information carried by a binary quantum system such as a spin-½ particle.

real photon: In quantum electrodynamics, a photon in a Feynman diagram that connects to the "outside world" and thus is subject to measurement. The opposite of virtual photon.

Schrödinger equation: The equation discovered by Erwin Schrödinger tat controls how the quantum wave function behaves over time.

simple state: *See* **product state**.

snowflake principle: Heuristic principle that no 2 macroscopic objects are ever exactly the same in every detail.

spin: The internal angular momentum of a quantum particle, such as an electron. The spin of a particle can only have values of 0, $^1/_2$, 1, $^3/_2$, 2, etc. (in units of $h/2\pi$).

spin component: The total amount of spin angular momentum parallel to a particular axis in space. For a quantum spin-½ particle, any component of spin can only have the values +½ or –½ (in units of $h/2\pi$).

spin-statistics connection: The physical principle that particles with spin 0, 1, 2, and so on must be bosons, while those with spin $^1/_2$, $^3/_2$, and so on must be fermions.

spontaneous emission: A process in which matter emits a photon, even without the presence of other photons.

state: A physical situation for a quantum system, described by a ket.

Stern-Gerlach apparatus: A laboratory device in which a particle with spin is passed through an inhomoheneous magnetic field. This permits us to measure the particle's spin along any 1 axis we choose (but not along all axes at the same time).

stimulated emission: A process in which matter emits a photon with the same wavelength and direction as some already existing photons. The more photons are present, the more likely this process becomes.

sum-over-histories: An approach to quantum mechanics developed by Richard Feynman. An electron going from here to there makes all possible paths, each one contributing its own amplitude to the process. The total amplitude gives the total probability for the trip.

superconductivity: The phenomenon of zero electrical resistance in some materials at very low temperatures. Such materials are called superconductors. Superconductivity is due to the superfluid-like properties of Cooper pairs of electrons in the material.

superfluid: A liquid at extremely low temperatures that has many surprising properties, including zero viscosity.

superposition: A combination of basis states, written: $a|state\ 1\rangle + b|state\ 2\rangle + \ldots.$

superstring theory: A contemporary speculative theory of elementary particles and their interactions, developed within the general framework of quantum theory.

symmetric: The mathematical property of the quantum state of bosons, which is unchanged when 2 identical particles are swapped.

system: Any part of the quantum world that we wish to consider. A system may include 1 or more particles.

thermodynamics: The branch of physics that deals with heat and energy transformations.

thought experiment: A highly idealized experiment that is used to illustrate physical principles.

ultraviolet catastrophe: A prediction of classical physics that a blackbody should emit more and more intensely at higher and higher frequencies. This prediction is not correct.

uncertainty principle: The principle discovered by Heisenberg in 1927 that sets a fundamental trade-off between how precisely a particle's position and momentum may be defined. This is sometimes expressed by the relation $\Delta x \Delta p \geq h$. A variation of the principle gives a trade-off between uncertainties in energy and time.

vacuum: The physical situation in which no particles are present. In quantum theory, the vacuum actually contains considerable energy.

Van der Waals force: The "stickiness" between atoms and molecules that causes them to condense into liquids and solids at low temperatures.

vertex: A point in a Feynman diagram representing a photon interacting with an electron or a positron.

virtual photons: In QED, an internal photon in a Feynman diagram. Such photons can never be directly observed. The energy in a virtual photon is "borrowed," subject to the terms of the uncertainty principle.

wave: A periodic disturbance, such as sound. Waves may either be traveling (like a moving sound wave) or standing (like the vibrations of a wire with fixed ends).

wave function: The mathematical function, usually denoted Ψ, that describes how a quantum wave depends on space and time.

wavelength: The distance between adjacent crests in a wave.

wave-particle duality: The idea that light can show wave and particle characteristics in different experiments. Later, this idea was extended to matter as well.

zero-point energy: The energy present in any quantum system, even in its ground state, due to the uncertainty principle.

zero total spin state: A special state of a pair of spin-½ particles. If the same spin component is measured on the 2 particles, opposite results are always obtained. This state is useful for studying the properties of quantum enlargement.

Biographical Notes

Aristotle (384-322 BC): Greek philosopher and polymath; the most notable pupil of Plato. Aristotle had one of the widest-ranging intellects in human history. His works on logic, metaphysics, science, medicine, ethics, and law established systems of thought that remain influential to this day. Aristotle believed that matter comprises 5 basic elements (earth, air, fire, water and a fifth element found in the heavens). However, he viewed these as continuous substances, not discrete atoms.

Babbage, Charles (1791-1871): English mathematician and engineer. Babbage, the son of a banker, studied mathematics at Cambridge. He spent his subsequent career trying to create mechanical calculating "engines" of increasing complexity. His designs followed principles closely resembling those of modern electronic computers, but the mechanical technology of 19th-century England was not advanced enough to realize his most ambitious designs. His Difference Engine, abandoned, was designed to compute the values of complex mathematical functions. His more complex Analytical Engine would have been a computer of a much more general and powerful sort. With different "programs" (encoded on punch cards), the Analytical Engine would have been capable of any sort of calculation at all. Non of Babbage's engines were completed during his lifetime, but a working model of Difference Engine No. 2 (designed in 1849) was finally constructed in 2002.

Bardeen, John 1908-1991): American physicist and one of the few individuals in history to win two Nobel Prices, one in 1956 and the other in 1972. The first was with W. Shockley and W. Brattain for the discovery of the transistor, which revolutionized electronics. The second was with Leon Cooper and John Robert Schrieffer for their "BCS" theory of superconductivity, a phenomenon that had been first observed as long ago as 1911. Bardeen spent the early part of his career at Bell Labs, then moved to the University of Illinois.

Bell, John (1928-1990): British physicist. Although he was trained and worked as a particle physicist, spending most of his career at the European particle physics lab CERN in Geneva. Bell found time to think deeply about the foundations of quantum theory. Inspired by the work of David Bohm on hidden variables, he did a careful reanalysis of the argument of Einstein, Podolsky, and Rosen. In 1964 he proved his remarkable theorem, stating that no mechanism of local hidden variables could ever reproduce the statistical correlations between entangled quantum systems. The exact conclusion to be drawn from this has been a subject of debate ever since; Bell's own view seems to have been that the concept of locality could not be maintained in quantum theory.

Bennett, Charles (b. 1943): American physicist and computer scientist. Bennett has been among the most profound thinkers about the physical nature of information and computation. In the 1970s, he showed that any computation can be done by a computer that operates in a thermodynamically reversible way – that is, with arbitrarily little "waste heat." With Gilles Brassard, he developed the BB84 scheme for quantum key distribution, essentially founding quantum cryptography. Later, in his office at EBM, he built the first working demonstration of the BB84 method. Bennett helped to discover quantum teleportation, dense coding, entanglement "distillation," and a host of other basic ideas in quantum information theory. Bennett is known for his creativity, his collegiality, his ability to communicate (one colleague admiringly called him a "troubadour") and his unfailing sense of humor. He has sent his career at IBM Research.

Bohm David (1917-1992): American-born physicist who later became a British subject, After service on the Manhattan Project during World War II, Bohm was called upon to testify before the House Un-American Activities Committee. He declined, invoking the Fifth Amendment, leading to his suspension from the faculty of Princeton University. Bohm left the United States and eventually settled in England. Meanwhile, Bohm did important research on the basic concepts of quantum theory. He proved that a hidden-variables theory could in principle reproduce the observed phenomena of quantum mechanics. With Yakir Aharonov, Bohm demonstrated that a quantum particle can respond to a magnetic field even if the particle has zero probability of being found in the region of the field. This Aharonov-Bohm effect is one of the great insights of modern mathematical physics and has led to a deeper understanding of so-called gauge fields. In his writings, Bohm was unafraid to engage deep philosophical questions about the nature of the world and the human condition. Bohm's work on hidden variables in quantum theory, together with his classic discussion of the EPR argument, later inspired John Bell.

Bohr, Niels (1885-1962): Danish physicist and one of the fathers of quantum mechanics. After receiving his doctorate in Denmark, Bohr spent several years in England, where he worked for Ernest Rutherford. Bohr applied quantum ideas to atomic structure, explaining atomic spectra by the discrete orbits allowed for the electron in the atom. After returning to Denmark, he established the Institute for Theoretical Physics in Copenhagen. This became the center of work on the new quantum physics, and young physicists from all over Europe and America studied and worked there. While others such as Heisenberg and Schrödinger created the mathematical theory of quantum mechanics, Bohr carefully laid its conceptual foundations. His principle of complementarity, the foundation of the so-called Copenhagen interpretation of quantum mechanics, allowed physicists to use the strange new concepts without contradictions. His fierce but friendly debate with Einstein about the nature and meaning of quantum physics explored many of the puzzles of the quantum realm. He was awarded a Nobel Price in 1922. In 1939, on the eve of World War II, Bohr and John Wheeler developed the liquid-drop model of the atomic nucleus, the basis for the theory of nuclear fission. Bohr spent the first part of the war in occupied Copenhagen, but then, forced to make a daring escape because of his Jewish ancestry, he participated in the US Manhattan Project to develop the nuclear bomb. After the war, he returned to Denmark. Bohr's ideas and personality were tremendously influential among theoretical physicists. He was always ready to consider radical new thinking; to one colleague, he said, "Your theory is crazy, but not crazy enough to be true."

Boltzmann, Ludwig (1844-1906): Brilliant but troubled Austrian physicist, most notable for his work in connecting atomic theory to macroscopic physics. Boltzmann showed how very simple assumptions about the chaotic world of atoms and molecules lead to detailed predictions about the laws of gas behavior, together with many other phenomena. He was often involved in controversy and left the University of Vienna for some years due to a dispute with his fellow professor, Ernst Mach. Boltzmann suffered from bouts of severe depression, however, and a few years after his return to Vienna he committed suicide. On his tombstone in Vienna is inscribed his greatest discovery, a mathematical relation between the thermodynamic concept of entropy and the statistics of the microscopic world.

Born, Max (1882-1970): German physicist who later became a British subject and who contributed decisively to the development of quantum theory. Born assisted Heisenberg in developing the mathematics of his version of quantum mechanics. He also provided a key insight for the interpretation of the waves in de Broglie and Schrödinger's version: the Born rule, which states that the intensity of the wave at a point determines the probability of finding a particle there. Born taught for many years at the University of Göttingen, and among his student and postdoctoral assistants are numbered many of the most famous names in 20th-century physics. He received a Nobel Price in 1954.

Bose, Satyendra (1894-1974): Indian physicist most notable for the discovery, in 1922, of the statistical laws governing one type of identical particle. Bose made his discovery in the middle of a lecture at the University of Dakha, in which he was attempting to demonstrate that classical statistical physics could not explain Planck's blackbody radiation law. During the lecture he made a "mistake" that unexpectedly led to the correct answer. Bose soon realized that he had stumbled on a new insight into the quantum world. Bose sent his paper to Einstein, who recognized it as an important contribution, saw to its publication, and worked to develop its ideas further. Bose became an important figure in the growth of science in India.

Brassard, Gilles (b. 1955): Canadian computer scientist at the University of Montreal. Brassard started out studying the mathematics of cryptography, but his collaboration with Charles Bennett on the BB84 protocol in quantum cryptography soon made him into a quantum physicist. He helped to discover quantum teleportation – indeed, it was invented at a workshop that he hosted at the University of Montreal. Brassard has also made fundamental contributions to entanglement "distillation" and the theory of quantum computing.

Casimir, Hendrik (1909-2000): Dutch physicist who contributed to both low-temperature physics and quantum electrodynamics. Casimir studied with the great Paul Ehrenfest, then worked with Bohr in Copenhagen and Pauli in Zurich. Although he was an industrial scientist, directing the Philips Research Laboratories in the Netherlands, he made numerous contributions to pure research. In 1948 he predicted the phenomenon that later bore his name (the Casimir effect), in which 2 metal plates are attracted to each other due to their modification of the quantum vacuum.

Cooper, Leon (b. 1930): American physicist who helped discover the mechanism of superconductivity and received a Nobel Price in 1972. Cooper proposed that electrons in a superconductor join up in pairs, later called "Cooper pairs," that behave as bosons in a superfluid. This allows the material to conduct electricity without resistance. Cooper is a faculty member at Brown University, where he has most recently done research in theoretical neuroscience.

Dalton, John (1766-1844): English chemist and the father of modern atomic theory. After studying the known facts of chemical composition, Dalton proposed in 1803 that elements are made up of atoms of a uniform mass, that the atoms of different elements have different masses, and that these atoms combine in definite ways to create chemical compounds. The atoms themselves are neither created nor destroyed in a chemical process but simply change their combinations. This idea revolutionized chemistry and shed new light on the behavior of gases.

de Broglie, Louis (1892-1987): French physicist who, in one of the most influential doctoral dissertations in history, proposed that electrons and other quantum particles must have wave characteristics. De Broglie's work "closed the circle" of quantum ideas and in short order became the basis for the wave mechanics of Schrödinger. De Broglie, who was a member of the French nobility, received a Nobel Prize in 1929 and became one of the most eminent men in European science after World War II.

Democritus (c. 460-370 BC): Greed natural philosopher and one of the originators of "atomism," the idea that everything in the world is made of tiny, indivisible units. Democritus's theory is summarized in a famous quotation: "By convention there is sweet, by convention there is bitter, by convention hot and cold, by convention color; but in reality there are only atoms and the void."

Deutsch, David (b. 1953): Israeli-English physicist and one of the most creative and eccentric thinkers in contemporary quantum theory. Long a proponent of Everett's many-worlds interpretation of quantum mechanics, Deutsch became interested in the idea of a quantum computer. An intelligent quantum computer, he reasoned, could be a type of observer that was "aware" of the branching of the universe's quantum state. His development of the theory of quantum computing led to the discovery of the Deutsch-Jozsa problem, which in turn sparked widespread interest in the powers of quantum computers. Deutsch has also applied his combination of rigorous mathematics and powerful imagination to other topics, such as the quantum physics of time machines. Deutsch is affiliated with, but not a faculty member at, Oxford University. He is seldom seen outside of Oxford, but his ideas are closely followed by quantum physicists worldwide.

Dieks, Dennis (b. 20th century): Dutch philosopher of physics. Trained as a theoretical physicist. Dieks has spent his career studying the philosophical aspects of relativity and quantum physics. In 1982 he proved the quantum no-cloning theorem independently of William Wootters and Wojciech Zurek, using a different mathematical method. He is a member of the philosophy faculty at the University of Utrecht.

Dirac, Paul (1902-1984): English physicist who contributed deeply to the mathematical tools of quantum theory and received a Nobel Price in 1933. As a graduate student at Cambridge University in the 1920s, Dirac seized upon the new theories of Heisenberg and Schrödinger, demonstrating their mathematical equivalence. The "ket" notation for quantum states used in our lectures was introduced by Dirac. In 1928 he proposed a new form of quantum theory compatible with Einstein's special theory of relativity, including a relativistic version of the Schrödinger equation later known as the Dirac equation. Consideration of this equation led Dirac to predict the existence of antiparticles. These were discovered only a few years later in studies of cosmic rays. Dirac laid the groundwork for the quantum theory of fields (including quantum electrodynamics) and was one of the first to analyze the statistical properties of identical particles – to mention only 2 of his remarkable contributions. For over 30 years he held Newton's old post as Lucasian Professor of Mathematics at Cambridge. Dirac's scientific work was guided by a passionate belief in the mathematical elegance of nature. His is buried in Florida, where he spent the last decade of his life, but his monument in Westminster Abbey is just a few steps form Newton's tomb.

Einstein, Albert (1879-1955): German physicist, later an American citizen, whose epoch-making contributions to physics during the early 20th century turned him into a public icon of a scientific genius. His fame was entirely deserved. In a series of brilliant papers in 1905, the young Einstein (then working as a patent clerk in Switzerland) made fundamental discoveries in statistical mechanics, established the special theory of relativity, and used Planck's quantum hypothesis to explain the photoelectric effect. More contributions followed, including his quantum explanation of the heat capacities of solids, many papers on the interaction of light with matter, and the statistical behavior of identical particles. Einstein's 1915 discovery of the general theory of relativity which explains gravitation as the curvature of space and time, was as astonishing as it was profound. The confirmation of this theory came a few years later, just after World War I, when the deflection of starlight by the Sun's gravity was precisely measured. This was the event that catapulted Einstein to international celebrity. He received a Nobel Price in 1921. Although Einstein was one of the pioneers of quantum theory, he later became its sharpest critic. His debates with Bohr at the 1927 and 1930 Solvay conferences were decisive turning points in the history of the subject. Einstein, a Jew, left Europe for America in 1932 and never returned. In 1935, Einstein, Podolsky, and Rosen argued that the phenomenon of quantum entanglement proved that quantum theory was an incomplete description of reality. (This argument, and Bohr's subtle reply, led John Bell to his remarkable work 3 decades later.) In later years, Einstein worked unsuccessfully to combine the known laws of physics into a "unified field theory." Einstein was never fully reconciled with quantum physics, never quite accepting that God "played dice with the Universe." In all of his scientific work, he was guided by the maxim, "The Lord God is subtle, but He is not malicious."

Everett, Hugh, III (1930-1982): American physicist. As a student of John Wheeler at Princeton in 1957, Everett developed the many-worlds interpretation of quantum mechanics. He saw this interpretation as a way to avoid the problems of the Copenhagen interpretation and give a solid framework for applying quantum theory to Einstein's general relativity (a problem still unsolved today). In the same PhD thesis, Everett also pioneered the use of concepts from information theory in the analysis of quantum systems. Possibly discouraged by the cool reception his ideas received from most physicists. Everett switched fields and spent the rest of his career doing operations research for the US defense establishment. His departure from physics research and his early death at age 51 deprived the world – this one, anyway – of a radical and creative thinker about the meaning of quantum theory.

Fermi, Enrico (1901-1954): Italian physicist, later American citizen, who made brilliant contributions to both theoretical and experimental physics. In 1926, while still in Rome, Fermi helped to develop the statistical theory of identical particles such as electrons that obey the Pauli exclusion principle. Later he became even more famous for his remarkable experiments on neutron-induced nuclear transformation, for which he won the Nobel Prize in 1938 and in which hi narrowly missed discovering nuclear fission. His groundbreaking theory of beta decay included Pauli's undiscovered "ghost" particle, which Fermi christened the "neutrino." After leaving fascist Italy and emigrating to the United States, Fermi worked on the Manhattan Project. His experimental reactor achieved the first sustained nuclear chain reaction in 1942.

Feynman, Richard (1918-1988): American physicist whose astounding scientific insight and quirky personality left an indelible stamp on 20th-century physics. As a graduate student of John Wheeler in 1942, Feynman developed his "sum-over-histories" approach to quantum mechanics. Like so many physicists, he worked on the Manhattan Project to develop the atomic bomb during World War II. Returning to theoretical pursuits after the war, he made decisive contributions to the development of quantum electrodynamics, introducing the remarkable Feynman diagrams to assist in calculations. He also made advances in the theory of superfluids and superconductors, in the theory of weak nuclear interactions, and in the quark model of nucleons, receiving a Nobel Prize in 1965. Feynman spent most of his career as a faculty member at Caltech, where he became a legend as a brilliant teacher. His 3-volume *Lectures on Phys-*

ics is standard equipment on any physicist's bookshelf. Feynman had the knack of seeing new possibilities in nature; both nanotechnology and quantum computing trace their origins in part to lectures given by Feynman. Many people first heard of Feynman during his work on the commission investigating the loss of the space shuttle *Challenger* in 1986; Feynman performed a dramatic demonstration using a clamp, a sample of material from the shuttle, and a glass of ice water that identified the root because of the disaster. He was a remarkable raconteur, and his books of personal reminiscences gained a wide audience. It was said that Feynman's graduate students at Caltech learned 3 tings from him: theoretical physics, save-cracking (a talent Feynman had developed playing pranks on the security officers at Los Alamos during the war), and bongo drumming.

Grover, Lov (b. 1961): Indian-American computer scientist. Like Peter Shor, a fellow computer scientist at Bell Labs, Grover began moonlight as a quantum physicist, studying the emerging field of quantum computing. In 1966 he discovered his quantum search algorithm, which would allow a quantum computer to "fin a needle in a haystack" far more rapidly than any classical computer.

Heisenberg, Werner (1901-1976): German physicist and one of the creators of quantum mechanics. In 1924-1925, Heisenberg came to Copenhagen to work with Bohr on the new physics. There he discovered his own highly abstract version of quantum mechanics, which came to be called "matrix mechanics." Although the mathematics of the theory was very strange, it soon became clear that it gave a precise account of the strange behavior of the microscopic realm. The theory was at first seen as a competitor to Schrödinger's wave mechanics, until Paul Dirac showed that they were mathematically equivalent. Heisenberg also formulated the famous "uncertainty principle," which establishes limits on our ability to know about the microscopic world. Heisenberg later made fundamental contributions to quantum field theory, nuclear physics, and elementary particle physics. He received a Nobel Price in 1932. During World War II, Heisenberg remained in Nazi Germany and directed part of the German nuclear program. This later led to considerable strain on his relationships with physicists from other countries, and his long friendship with Niels Bohr came to an end. After the war, Heisenberg wrote extensively about the philosophical ideas embedded in quantum theory.

Huygens, Christiaan (1629-1695): Dutch physicist and astronomer. As an astronomer, Huygens discovered Saturn's rings and its largest moon, Titan. As a mathematician, he contributed to the foundations of probability theory. As an inventor, he was responsible for several advances in the construction of accurate clocks. But it was as a physicist that he made his most notable contributions. Huygens was particularly interested in the nature of light, which he regarded as a wave phenomenon like sound. He introduced what is now called the "Huygens principle," which states that each point on a traveling wave front acts as a source for further waves. This principle allowed him to analyze the reflection and refraction of light based on his wave theory.

Jozsa, Richard (b. 20th century): British mathematician and physicist. After studying mathematical physics with the great Roger Penrose, Jozsa worked with David Deutsch on what came to be called the "Deutsch-Jozsa problem," the first-proposed mathematical problem that could be solved more efficiently by a quantum computer than by any classical one. He also helped to invent quantum teleportation. Jozsa is now a professor in the Department of Computer Science at the University of Bristol.

Maxwell, James Clerk (1831-1879): Scottish mathematician and physicist who made fundamental contributions to mechanics and electromagnetism. Maxwell applied Newtonian mechanics to the behavior of huge numbers of colliding molecules, deriving the statistical distribution of molecular speeds in a gas. He also derived many useful mathematical relations in the science of thermodynamics. By collecting together and analyzing the known laws of electromagnetism, Maxwell realized that the system was mathematically incomplete. When he supplied the missing pieces, he discovered that electromagnetic disturbances would travel trough space in the form of polarized waves with a speed equal to that of light. He concluded that light is an electromagnetic wave, an idea that unified optics and electromagnetism, and his work indicated the possible existence of other related waves. The later discovery by H. Hertz of radio waves vindicated Maxwell's theory. Maxwell himself was a religious man, a guitar player, and the author of several amusing songs about physics and its study.

Newton, Isaac (1642-1727): English physicist and mathematician and without doubt the greatest scientific mind of his age. In his book *Mathematical Principles of Natural Philosophy* (1687), Newton established the science of mechanics based on universal laws of motion and gravitation. This work explained motions ranging from projectiles on Earth to the orbits of the planets, together with a host of other phenomena. Newton invented calculus, which he called "the method of fluxions," to deal with his new system of mechanics. Newtonian mechanics was the basis for physics for more than 2 centuries. Newton also made tremendous contributions to optics, including the invention of the reflecting telescope and the discovery that white light is a mixture of all colors. Newton's view, expounded in his book *Opticks* (1704), was that light was a stream of discrete corpuscles. In this he disagreed with the wave view of Huygens and others, but the matter was not settled experimentally for another century. In addition to his scientific pursuits, Newton commented on scripture, wrote about theology, and studied alchemy. Newton was a powerful and influential figure in the English science of his day and served as president of the Royal Society of London from 1701 until his death.

Pauli, Wolfgang (1900-1058): Austrian physicist, later and American citizen and a resident of Switzerland, and winner of a Nobel Prize in 1945; famous for his brilliant discoveries in theoretical physics and his sharp critique of shaky reasoning. Pauli developed his "exclusion principle" in 1924 to explain the structure of many-electron atoms. He was the first to use Heisenberg's quantum mechanics to explain atomic spectra, and he contributed a great deal to the theory of particle spin. He also proved the "spin-statistics" theorem, the connection between a particle's spin and its character as a boson or fermion. In 1929 he proposed that the mysteries of beta decay (one of the main types of radioactivity) could be explained by the existence of an almost-invisible "ghost particle," later called the neutrino by Fermi. (When the neutrino was finally discovered almost 30 years later, the discoverers sent a telegram congratulating Pauli. His reply: "Thanks for the message. Everything comes to him who knows how to wait.") Pauli was well known for his ready and caustic wit, and anecdotes about his various remarks are favorites among physicists. (Of one paper he said, "This isn't right. This isn't even wrong.")

Peres, Asher (1934-2005): Israeli physicist. After a perilous childhood during World War II hiding out in occupied France, Peres emigrated to Israel, where he studied theoretical physics at Technion under Nathan Rosen, one of the authors of the EPR paper. Peres went on to be a faculty member at Technion and to make many contributions to physics, especially to the foundations of quantum theory. He drew attention to the fundamental role that the concept of information plays in the theory and later was one of the inventors of quantum teleportation. He was once asked by a reporter, "Can you teleport only the body, or also the spirit?" He replied, "Only the spirit."

Planck, Max (1858-1947): German physicist and the originator of the quantum hypothesis; winner of a Nobel Prize in 1918. For most of his career, Planck was a professor at the University of Berlin. In the last years of the 19th century, he turned his attention to the problem of understanding the electromagnetic radiation emitted by hot bodies of all sorts. Since all black bodies, regardless of composition, emit radiation with the same characteristics, Planck recognized this as a problem of fundamental importance. He early work met with only partial success. Finally, in 1900 he adopted the quantum hypothesis as, in his words, "an act of despair." Though it involved a radical departure from previous ideas about energy, Planck's new theory accounted for blackbody radiation with great exactness. Plank observed the subsequent development of quantum theory with great interest. With a sad wisdom, he wrote, "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

Rutherford, Ernest (1871-1937): New Zealand physicist and one of the great experimentalists in the history of science, he received a Nobel Prize in 1908. Though born in New Zealand, Rutherford spent most of his career in England. He identified the main kinds of radioactivity and discovered the law governing the rate of radioisotope decay. He supervised the scattering experiment of Hans Geiger and Ernest Marsden and correctly interpreted its results to construct the "solar system" model of the atom. Rutherford was the first researcher to produce an artificial transmutation of elements, using alpha particles to transform nitrogen into oxygen. Rutherford's students and assistants included many who won Nobel Prizes in their own right (including Niels Bohr). Rutherford had no false modesty about his remarkable accomplishments. When someone suggested that he had been lucky to ride "the crest of the wave" in discovering new physics, he answered, "Well, I made the wave, didn't I?" His untimely death in 1937 came when he was still at the height of his powers; just a few years earlier, his suggestion that the nucleus must contain a neutral particle had been confirmed by James Chadwick's discovery of the neutron.

Schrieffer, John Robert (b. 1931): American physicist who, as a graduate student at the University of Illinois, helped to formulate the theory of superconductivity; he received a Nobel Prize in 1972. Schrieffer figured out how to describe the flow of Cooper's electron pairs through a material. He holds posts as a professor of physics at universities in both California and Florida.

Schrödinger, Erwin (1887-1962): Austrian physicist and one of the developers of quantum mechanics. Schrödinger's version, called "wave mechanics," was at first seen as a competitor to Heisenberg's wave mechanics, before Paul Dirac showed them to be mathematically equivalent. His basic equation, the Schrödinger equation, is one of the most fundamental relations of mathematical physics. Like so many of his physicists of Germany, Italy, and Austria, Schrödinger was obliged to leave in the early 1930s as the Nazis took power, he settled in Dublin, founding the institute for Advanced Study at the university there and writing an influential book, *What is Life?*, about the physical nature of biological systems. This book inspired physicist Francis Crick to switch fields and become one of the discoverers of the structure of DNA. Schrödinger returned to Vienna for the last few years of his life, Schrödinger received a Nobel Prize in 1933, but in the popular mind he is most strongly linked to his 1935 thought experiment in which a cat enters a quantum superposition of being alive and dead. He wrote, "The [quantum state] of the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts." (In his defense, one should note that this idea was introduced with the words, "One can even set up quite ridiculous cases.)

Shannon, Claude (1916-2001): American mathematician and engineer, founder of information theory, Shannon's many discoveries have been of incalculable importance in creating the "information age." His MIT master's thesis in 1937 laid the abstract groundwork for the digital computer. After World War II, he developed the mathematical theory of communication and soon applied it to everything from signal processing to human language to cryptography. He was a prolific inventor and game player, applying his genius to gambling, the stock market, and computer chess. Shannon did much of his work at Bell Labs, later joining the faculty at MIT.

Shore, Peter (b. 1959): American computer scientist who has made key discoveries in quantum computing and quantum information. As a computer scientist at Bell Labs, Shor became fascinated by the new idea of a quantum computer. In 1994 he discovered that a quantum computer algorithm could factor a large integer exponentially faster than any known procedure on a classical computer. Given the huge importance of the factoring problem in cryptography and number theory, this has provided much of the impetus for experimental work on quantum computers. Such computers are difficult to build, since their operation is very sensitive to environmental noise. Shor helped to find a possible answer, however: in 1995 he discovered the first method of "quantum error correction." Shor is now a professor of applied mathematics at MIT.

Wheeler, John (1911-2008): American physicist who made fundamental contributions to several areas of physics, from elementary particles to cosmology. Wheeler was deeply influenced by Niels Bohr, with whom he developed the theory of nuclear fission in 1939. An intensely patriotic man, he helped to develop both nuclear and thermonuclear weapons in the 1940s and 1950s. In the 1950s, Wheeler became interested in the implications of Einstein's general relativity. His work helped to revive the field of gravitational physics, and in 1967 he coined the term "black hole" to describe a completely collapsed star. Though he mentioned Hugh Everett III in the creation of the many-worlds interpretation, Wheeler eventually rejected it and came to espouse a version of Bohr's Copenhagen interpretation. For Wheeler, the world itself comes into being through innumerable "elementary quantum phenomena." These elementary quantum phenomena are themselves not localized in space and time – as illustrated by his "delayed-choice experiment" – but from the real underlying structure of space, time, matter, and energy. The world is therefore essentially made of information – an idea Wheeler christened "it from bit." Wheeler was famous for his penetrating (if slightly oddball) questions and his striking way of expressing ideas in phrases and images. He spent most of his career at Princeton

University, with a 10-year sojourn at the University of Texas. Wheeler was teacher and mentor to many physicists mention in this course, including Richard Feynman, Hugh Everett III, Wojciech Zurek, William Wootters and your lecturer.

Wootters, William (b. 20th century): American physicist. While a graduate student at the University of Texas, Wootters, together with Wojciech Zurek, proved the quantum no-cloning theorem. Under the influence of John Wheeler, he became fascinated by the relation between quantum physics and information. He helped to discover quantum teleportation and protocols by which noisy entanglement may be "distilled," among many other contributions to quantum information theory. Wootters is a professor of physics at Williams College.

Young, Thomas (1773-1829): English physicist and polymath. Yong was a physician who contributed to many areas of science, including the theory of elasticity. He is most famous for his decisive 2-slit experiment (performed in 1801) that demonstrated the wave nature of light and measured its wavelength. This experiment settled for a century the long-standing debate about whether light was made of continuous waves or discrete corpuscles. Young was also a linguist who made fundamental contributions to reading the Rosetta Stone, laying the ground work for Champollion's later decipherment of Egyptian hieroglyphs.

Zurek, Wojciech (b. 1951): Polish physicist, now an American citizen, who has made contributions to statistical physics, quantum mechanics, black holes, and cosmology. Long interested in the relation between information and quantum physics, he proved (with William Wootters) the quantum no-cloning theorem and has long studied quantum decoherence. Decoherence is the process by which the environment of a system, by constantly "monitoring" it, destroys the coherence of quantum superpositions. Zurek is presently a researcher at Los Alamos National Laboratory.■

Fisheries *from page 3*

Whether the next three years of cutbacks will mean substantially less science for the Arctic is a question Dr. Wheatley "can't speak to." But she says there is some new federal money. Though hardly large amounts, the funds will help to identify Arctic undersea areas most at risk from climate change and pay for international and fisheries boundary projects.

"We will never be able to do everything," she says. "There's always more information that could be collected."

Mr. Lynch, Nunavut's fisheries director, is not so philosophical. "DFO is walking away from a lot of science and research in Nunavut, which is a shame," he says. "The problem is that we're at the tail end of a lot of DFO programs that have really helped fisheries on the East and West Coast.… The programs are ending, and we're just getting started."

Nunavut has been developing its own science program, Mr. Lynch says. Last year, for instance, it launched a 64-foot research vessel to explore new fishing grounds as well as conduct other science, such as work (with DFO researchers and others) to reduce the incidental catch of Greenland sharks.

"You can't have a sustainable fishery without good science. We know that," Mr. Lynch insists. Any suggestion that the Eastern Arctic fishery is reckless and should be stopped is simply irresponsible, he says.

"We've got a growing population in Nunavut looking for nutritional food sources as well as employment. How can you not?" he argues. "It's like telling a developing country you can't farm because you're hurting the land. To me, there's got to be a balance," he continues.

"I think you have to walk in another person's shoes before you can make blanket statements about stopping every development in Baffin Bay. That's just silliness. It's just silly. People have been whaling and sealing here for millennia."

Back in Pangnirtung, talk around the Auyuittuq Lodge – the town's only hotel, a few steps away from the mayor's office – is more about the not-yet-finished harbour than about the adequacy of fisheries science.

Under the lodge's wide windows facing the towering cliffs of the fjord, a few locals are gathered for coffee. The winter-fishing season went particularly well (thanks to solid, lasting ice) and some are musing about whether a significant summer fishery might also soon be in the cards.

The town's new small-craft harbour, which could be completed as soon as this autumn, is expected to help accommodate a summertime fishing fleet in Cumberland Sound. The project is being paid for, in part, through a $25 million investment from Ottawa – Prime Minister Stephen Harper trumpeted Arctic fishing's great economic potential when he visited the community in 2009.

With active summer fishing, production at the Pangnirtung Fisheries Ltd. plant could almost double. "That's really where the fishery should be heading, and it is heading there," says general manager Don Cunningham.

For scientists who argue a flourishing Arctic fishery is ecologically risky and possibly a disaster, none of this will sound like good news. But the Arctic can be a land of stark choices.

"The truth is," Mr. Cunningham says, "there just aren't a lot of other options up here for people."

Our Comment

What our society is drastically short of are the trained human resources closer to home that we once had recognized – from the lessons learned millennia ago from the ancient Greeks – that would have given us the qualified human capital resources needed for dealing with a quite new set of human resources – that we denied ourselves in the interest of speculative banking. Before we can marshal the resources to handle the dauntingly unknown environment of the arctic, we have need of a system of social accountancy, of which speculative banks were allowed to deprive us. *W.K.*