FROM THE JULY 2003 ISSUE

Discover Dialogue: Geneticist James Watson

James Watson's solution: 'Just let all the genetic decisions be made by women'

By David Ewing Duncan | Tuesday, July 01, 2003

RELATED TAGS: GENETICS

Fifty years ago, two unknown molecular biologists at the Cavendish Laboratory at Cambridge University had one of the great eureka moments in the history of science: They discovered that DNA is organized in the shape of a double helix—two intertwining strands of nucleotides on a superstructure of sugar. Only 25 years old then, James Watson was a stringy, thin biologist with wavy hair and a desire to be famous. Born in 1928, he graduated from the University of Chicago at age 19 and got his Ph.D. at Indiana University at 22. In 1962 he, Francis Crick, and Maurice Wilkins won the Nobel Prize for their discovery. In the intervening years, Watson has remained a key figure in genetics,serving as the president of Cold Spring Harbor Laboratory on Long Island and as the original director of the Human Genome Project. In this spirited interview with author David Ewing Duncan, he reinforces his position as a powerful, independent force in biology.

What are you most proud of?

W: My textbook *The Molecular Biology of the Gene* and my book *The Double Helix*.

Not the actual discovery of the double helix?

W: No, because the double helix was going to be found in the next year or two. It was just waiting to be found, and I was the one who finally found it because I was the most obsessed about it.

How do you account for what you've accomplished?

W: Ambition. You want to get things done. And you want your university or your school to be good; you want to do important things. And you see that society will be helped, and so to what extent you say: I'm just trying to push myself. . . . Francis Crick and I both wanted to do big things. If you succeed with your first dream, it helps. You know,people trust you, possibly, for the second one. They give you a chance to play out your second one.

Why did you choose to write a book focusing more on the people involved rather than the science of the double helix?

W:I wanted to see if I could write a good book. It was ahead of its time,you could say, in terms of style. I wasn't thinking of myself as a scientist, you know. My heroes were never scientists. They were Graham Greene and Christopher Isherwood, you know, good writers.

Did it bother you that some people found your descriptions of them to be somewhat critical?

W: No one said my descriptions were wrong; they just said I shouldn't have had them. Francis Crick and I talked that way.

What about Rosalind Franklin? Do you think she got the credit she deserved?

W: She died too soon. We didn't get much credit for those first five years. You know, we knew we'd done something big, but the Meselson-Stahl experiment hadn't been done, which confirmed the double helix in 1958. She died in 1958. . . . It was sad when she got ovarian cancer. But you know, if she'd just talked to Francis, he would have told her what we were thinking. And she would have solved the structural problem. If she had shared her evidence, he would have told her what it meant. She would have gone back and found the double helix. But she didn't want to speak to us. We were the enemy.

It must have been hard for a woman in the boys'-club atmosphere at Cambridge at the time.

W: I thought she was rather dowdy. I didn't dislike her or anything like that. We never got a chance to know each other.

Should she have shared in the Nobel?

W: Some people have said that we should have shared the glory with her. .. . It's true that when I saw her photograph [of DNA], that galvanized me into action. But then people think it was all the details of the photograph that gave me the answer. It wasn't that; it's too complicated to go into. But she never held it against Francis when she was dying. She went to stay in his house. But they never talked about it. Francis says they were concerned with the future, not the past.

I've been told by some geneticists that humans are essentially organic machines and that one day we will understand how we work. If so, what happens to that unexplainable mystery of what makes us human, where we draw our passion, our poetry—our soul, if you will?

W: The luckiest thing that ever happened to me was that my father didn't believe in God, and so he had no hang-ups about souls. I see ourselves as products of evolution, which itself is a great mystery.

What about the impact of genetics on emotions?

W: Take love. At the end of it, love doesn't come from God, so it's not the greatest gift of God but the greatest gift of our genes. You see evidence of maternal care in birds, and they feel seemingly pretty strong about it. So it's an emotion that has an enormous selective advantage. You've probably met someone who you think is just not capable of love. I suspect that they lack a gene that is necessary for the emotion.

Does the lack of a love gene mean these people will lose out in evolution?

W: No, as long as you've got a good brain, you can marry for money. There are other strategies, so I'm sure there are a lot of loveless women in America.

What about other emotions—say, anger?

W: In several studies researchers have found a gene associated with violence. They found the gene can exist in two forms: the gene where you express a lot of the enzyme and the one where you express a little. Then they correlated that with what happened to children who were abused. If a child was abused and didn't have much of that enzyme, they had a much higher probability of getting into trouble with the law. If you weren't abused, the chance of your getting into trouble with the law was much, much slimmer. So most people, if they have a lot of the enzyme, the anger dissipates fast. If you come from a good family, then when you get angry, you don't hit someone in the face. I want to test myself because I bet I have the root form of the gene, but I keep it in the background.

Do you get angry?

W: Very fast.

Is it over with fast?

W: Yes.

What is the purpose of this anger gene?

W: It is extremely interesting to find out why some people have one personality and others are really different, because if there's one thing that doesn't seem to change during people's lives, it's their personality. If someone is phlegmatic, it's with them all their life. You can't change it.

Have you ever been tested for DNA markers for disease?

W: I haven't been. I had my mitochondrial DNA completely sequenced. I have a very common mitochondrion—the most common one. My Irish grandmother died in 1992 when she was in a nursing home; she was enraged for a year, and my mother couldn't handle it. So I suspect it was Alzheimer's. No one ever used the word, but she had become impossible to handle.

How do you feel about being tested for the Alzheimer's gene?

W: I don't want to know unless I can do something about it, so I'm acting as if I have the bad news.

Explain your theory of happiness.

W: My idea is we're dominated by our emotions. And emotions, you know, have chemical circuits. And these influence our genes, and this is not surprising—you might need different sorts of people in a stable society. Some people get angry, some people don't. The gene for endorphin makes up part of a protein called POMC. So this protein is broken down by proteases. On the one end are endorphins, but on the other end is melanocortin and what used to be called MSH. Now MSH is made when you're in the sun. So when you make MSH, you're also making endorphins. So my theory is that that's why the sun makes you happy. But if you're not in the su you're unhappy. So my theory of happiness is that there are emotions that have a selective advantage; they make you do things that are good for you.

What about manipulating things like happiness or, say, intelligence or memory—if this becomes possible? What if you were able to genetically enhance these things?

W: I think that would be great, because I think so many people hardly have the intelligence that lets them survive in our civilization. Maybe one of the reasons for this growing inequality of income may in some sense be a reflection of some people being more strong and healthy than others. Some people, no matter how much schooling you give them, will never really be up to what is now considered a necessary degree of effective intelligence. We're sitting at the top of the pyramid of an awful lot of things that happen without us knowing it, that allow us to be sitting here. We never ask what it's like to be at the bottom. There seems to be a total lack of compassion for people at the bottom.

In the 1990s we had the "digital divide" between the technology haves and the have-nots. What will happen when the wealthy have access to genetic enhancements but not the poor?

W: The function of genetics should be somehow to try to reverse bad truths. I think we need to develop a political philosophy about this, to establish rules. One is that some people fail for reasons out of their control. . . . What function of you is really caused by having a bad throw of the genetic dice?

Do you worry that through genetic engineering we may create a new subspecies of human who is stronger, smarter, and healthier, and that this new species will end up surviving while the current *Homo sapiens* dies out? Something like the situation with the Neanderthals and our ancestors, the Cro-Magnons?

W: No, I don't think so. It depends on how we approach it. I think some people may have to be helped. Whether it's getting the genes for mental illness out of their family, however you do it. You could add a gene that would make you resistant to HIV. Wouldn't that be a rather nice thing? But I'm not in favor of a "sterilizing the lower classes" kind of argument.

Let me jump to the next step of that: You are Jim Watson. You're put in charge of how we as a society are going to react to issues raised by genetics—stem cells, bioengineering, and the like. What would you do?

W: Well, my sensibility is very libertarian. Just let all genetic decisions be made by individual women. That is, never ask what's good for the country; ask what's good for the family. I don't know what's good for the country, but you can often say what's good or bad for the family. That is, mental disease is no good for any family. And so if there's a way of trying to fight that, I'd let a woman have the choice to do it or not do it. Not give in and have the state tell you to have a certain sort of child. I would be very frightened by the state telling you one way or the other.

What about some of the issues like stem cell cloning?

W: I think no president could withhold any treatment that works. Since we don't know whether stem cells will cure Parkinson's, you can, you know,wait and see what happens. But I don't have a problem with George Bush. He wants to be re-elected, and he may actually believe in God.

Do you have a fear that the momentum in research may shift to Europe?

W: No. The religious right is still only 20 percent of the country. And even there, if it was a question of whether they would have a healthy grandchild, they might choose a healthy grandchild.

Biotech claims to be about to deliver dozens of new drugs and therapies for everything from heart disease to cancer. How can we pay for this with a health care system already straining to pay for what we've got now?

W: We've got to find a fairly cheap way to cure cancer.

David Kessler, the former commissioner of the Food and Drug Administration, is calling for a big government-funded research project to help fill in the gaps in genetic pathways in people, which are turning out to be far more complex than expected for illnesses such as heart disease and which may be beyond the ability of private companies and smaller labs to figure out and pay for. Do you think this is necessary?

W: We should have gene expression and big projects organized by the National Institutes of Health, and they're not doing anything. We got the Human Genome Project done because we didn't work through a pre-existing institute but set an institute up to do big projects.

Looking around your office here, I notice that you have a copy of *Gattaca* on your desk.

W: Awfully good movie. It was pretty clever.

What do you think of the world that was depicted there? Is that something we'll see, do you think, or a version of it?

W: No. See, the reality is that we are genetically very unequal now.

So a version of *Gattaca* already exists today.

W: A version is already here.

All men are created equal, but . . .

W: Yeah. But you know, when he finally has a swimming race, he beats the brother.

+

FROM THE FEBRUARY 2004 ISSUE

Discover Interview: Planetary Scientist Alan Stern

The planets are the obvious next frontiers for human exploration

By Kathy A. Svitil | Monday, January 05, 2004

RELATED TAGS: SPACE FLIGHT

This summer, construction will begin on a probe to Pluto and the Kuiper belt. Planetary scientist Alan Stern, director of the Southwest Research Institute in Boulder, Colorado, is the principal investigator for the mission. He is also a licensed commercial pilot and was once a finalist for the position of space shuttle mission specialist. Stern has made a career of investigating the solar system's frontiers, from a mysterious band of asteroids that may be orbiting the sun inside Mercury to the vast Oort cloud far beyond the known planets, the source of all comets.

Did you ever think that a mission to Pluto wouldn't happen?

S: I had a lot of doubts through the 1990s, during Dan Golden's NASA administration, because NASA repeatedly cancel~~l~~ed missions to Pluto, despite the fact that the scientific community kept saying it was top priority, crucial to getting an understanding of our solar system. Now I am fairly convinced that it will happen.

Is Pluto a planet?

S: Of course it is a planet. The generally accepted definition of a planet is very simple: It is a body that orbits its star, and it has to be large enough to become round under self-gravity but not so large that hydrogen fusion takes place in its center. If the object is too large and fusion takes place, we call it a star. And if it's too small and its own gravity wouldn't make it round, we call it a rock. Pluto is about 10 times the size of the smallest object in space that would become round due to gravity, so it easily qualifies.

Why should we go there?

S: In part, we should go because exploration is part of what makes us human. Beyond that, we should go because it turns out that Pluto is at the nexus of four key scientific themes that will lead us to a better understanding of our solar system. One theme is that Pluto was the first to be discovered of an enormous collection of trans-Neptunian objects called the Kuiper belt. These bodies are part of a previously unknown portion of the solar system—what I like to call the third zone of the solar system. This third zone was on its way to growing a very large planet, but something—we don't know what—stopped the process. Instead we have a collection of miniature planets. That means that in this zone we can find planetary embryos that were frozen in time during their gestation. That gives us a window into the past. That's the second theme.

The third theme is that Pluto and its moon, Charon, which is half Pluto's size, constitute a binary planet. We think binary planets are common in the galaxy, just as we know that binary stars are common in the galaxy, and we have even begun to find binary asteroids. The *New Horizons* Pluto mission will be the first mission to a binary object and will help us understand everything from the origin of Earth's moon to the physics of mass transfer between binary stars.

Finally, Pluto has a knock-your-socks-off atmosphere that's escaping rapidly like a comet's, but on a planetary scale. As a result, the planet has shrunk in size over billions of years because of the same processes that shaped the early evolution of Earth's atmosphere and very likely that of both Mars and Venus. We have never been to a planet where this kind of rapid escape is taking place. By going to Pluto we have a chance to anchor, with real data, models of the early evolution of Earth's atmosphere.

What would people see if they went to Pluto and stood on the surface?

S: The surface is bright and covered in a fresh, pinkish snow. People commonly think that it would be dark on Pluto because it is so far from the sun, but it is actually about as bright as dusk here on Earth, with enough light for you to very easily read a book and see what's going on around you. On the Charon side of Pluto, you'd see a big old moon up in the sky, appearing 10 times as wide as Earth's moon and twice as bright. You might see mountains on Pluto. You'd certainly see craters. There may be volcanoes and geysers. You would from time to time see atmospheric phenomena such as fog, clouds, or hazes. If you were there long enough, you would see it snow.

What is the third zone of the solar system like?

S: The Kuiper belt region, which I call the third zone because it lies beyond the rocky terrestrial planets and beyond the giant planets, is a bizarre frontier. It is dotted by more than 100,000 miniature frozen worlds. Based on data already in hand, we suspect that most are made of rock and ice with a liberal dash of organic molecules. It appears that thousands of these bodies have moons. Some may even occasionally grow atmospheres. And the latest news is that the king of the Kuiper belt, the king of the third zone, Pluto, may even sport an ocean under its icy crust!

How much is out there at the edge of our solar system that we have not yet discovered?

S: The short answer is—a lot. The Kuiper belt is probably littered with hundreds, if not thousands, of ice-dwarf planets like Pluto. NASA has explored all four terrestrial planets and all four giant planets. But the number of bodies we'd classify as planets in the solar system is probably closer to 9,000 than it is to nine, and we haven't been to the most populous class of bodies at all—the ice-dwarf planets of the Kuiper belt. Even farther out, beyond the Kuiper belt, lies the Oort cloud, 1,000 times farther away. The Oort cloud consists of objects ejected from the region surrounding the giant planets during and after their formation. In the Oort cloud there may be large planets that were ejected from the solar system in the early days when Jupiter, Saturn, Uranus, and Neptune were muscling out their rivals.

Could there be objects as big as Jupiter or Saturn in the region beyond Pluto?

S: Not objects the size of Jupiter or Saturn because Jupiter and the other giant planets couldn't have ejected objects that large, but there certainly could be a handful of Earth- and Mars-size objects. There could be hundreds of things the size of Pluto in the Oort cloud, and a number of objects the size of ~~the~~ Earth or Mars.

How do we find them?

S: You have to look! Actually, anything in the Oort cloud is too faint to see with the technology we have today. For example, NASA's Spitzer Space Telescope, which launched in August-, can see an object the size of Pluto located a few hundred astronomical units away [one astronomical unit is 96 million miles—the distance from ~~the~~ Earth to the s~~S~~un], and Spitzer can detect a planet the size of Earth out to about 1,000 astronomical units. However, the Oort cloud is between 10,000 and 100,000 astronomical units away. So an Oort cloud survey will have to be the project of a future generation.

Can studying Pluto and these other objects tell us anything about Earth's formation and its history?

S: Yes, it can. The standard model for the formation of the Earth-moon system is that a huge, Mars-size object hit Earth and spun off material that coalesced in orbit to become the moon. The Pluto-Charon system is the only other place in our solar system where we believe this happened on a planetary scale. By going to a system like Pluto-Charon, we'll better understand how the Earth-moon system formed.

After Pluto, where else in the solar system would you like to explore?

S: I would like to see a robotic return mission to Uranus and Neptune. I'd like to see further robotic exploration of the Kuiper belt, and I'd like particularly to see humans go back to the moon for a serious exploration and then on to asteroids and Mars.

What are the vulcanoids?

S: The vulcanoids are a putative population of asteroids that may circle the sun inside the orbit of Mercury, like a little Kuiper belt, if you will, on the inside of the solar system. Instead of being icy, however, they are expected to be rocky because it is so hot. Although no object on such an orbit has been detected just yet, there is good reason to expect that they might exist. For example, the surface of Mercury is severely battered, and many of the projectiles that hit it may have been vulcanoids. The question is whether there are any left or whether they're all gone. We really don't know because it's a very, very difficult observational problem to detect these bodies, even with modern technology. The easiest way to look is from space, but that's very expensive. Doing it from the ground is extremely hard because one has to look for faint points of light against the twilight sky. Our group has taken a middle-ground approach by using high-altitude aircraft that can fly up into the high upper stratosphere where the sky is much darker, making the vulcanoids easier to detect. We haven't finished our search yet, so I can't yet tell you if there are vulcanoids. Stay tuned!

You've done these vulcanoid surveys and studies of other asteroids, meteors, and comets from the backseat of a high-performance aircraft, like a WB-57 or a F/A-18 Hornet fighter jet. Is there really a scientific benefit to working out of an F-18, or is it just a lot of fun?

S: It's both. I have to say that the grants that paid for the studies came through peer-review panels that throw out five of every six proposals. If this was purely so that I could have a good time in the backseat of a fighter, it wouldn't survive for 10 minutes in a peer-review panel.

My colleague Daniel Durda and I discovered a way to do certain kinds of astronomy from a jet that you just cannot do from the ground. You can do these studies from space, but this is 1,000 times cheaper, and 10 times cheaper than using a big aircraft like those NASA typically has flown around. And for the particular niche we are exploring, the jets we use do the trick.

As a pilot, do you ever get the itch to take the controls?

S: *Every* flight. Sometimes we even get to. But the mission isn't to let the astronomer fly; it's to accomplish specific observing goals with the gear we bring along.

Why do you focus on the solar system's small, low-profile bodies? Why not big-ticket items like Mars?

S: The smaller objects *are* big-ticket items! Understanding the architecture of our solar system is a pretty big-ticket item. Discovering whether or not there is an asteroid belt interior to Mercury's orbit, finding out whether or not the comets were crucial to the formation to life on Earth, doing the first mission to the last planet, Pluto—I consider these all big-ticket items. Just because Pluto or comets aren't as big as Jupiter doesn't mean they are not scientifically important—indeed, just the reverse is often true. Sometimes great things come in small packages.

But, honestly, the public just isn't that interested in comets or the Kuiper belt. Most people have never heard of vulcanoids.

S: I think you're right about the vulcanoids, but there are a lot of things people have never heard of that eventually come to be very important. Six hundred years ago, most people never heard of North America. Being a researcher doesn't mean that you follow what is publicly appealing, because public interest generally lags scientific understanding. It's our responsibility as research explorers to find out the lay of the land, not to follow a popularity contest about where our research should go.

What's the most important thing about astronomy that everyone should know but don't?

S: I'd say how ancient virtually everything is in space. Almost all of the galaxies, the stars, the planets, are billions of years old—a million times older than the Parthenon, and tens of millions of times older than the oldest human being who has ever lived. To me, that really puts a lot of things that happen in day-to-day life, or the news, in perspective. No matter how old you are, it makes you feel young. And—perhaps this is the best part—it makes you realize how audacious we are as a species that was "born yesterday" to think we can understand the universe!

What are we learning about comets?

S: Comets are very important in terms of the hazard they pose to Earth's ecosystems over geological time, and they're the best samples we have of the primordial material that formed the solar system. We know that comets bombarded Earth after its formation, and they brought a lot of water and more complex stuff to the young planet. Although I personally discount it, it is entirely possible that comets actually brought life to Earth—

microspores or something from other systems where life had evolved. We won't know until we bring back samples.

Many researchers who work on unmanned space projects take issue with all the money that goes into manned missions. You've worked both sides of the street. What's your take?

S: NASA's human exploration program did historic, even epic, things in the 1960s and early 1970s, but it has been on a leash ever since. We have the capability to do so much more, to do real geological field exploration of the moon and the asteroids and field expeditions to Mars. Instead, for the past three decades we've been relegated to nothing more than trips to low Earth orbit in space shuttles and a space station going around in circles growing plants and taking pictures of the weather. I hope that will change soon.

Why aren't we doing more?

S: The political will hasn't been there, and it's so unfortunate. I think human beings are truly explorers at heart. The planets are the obvious next frontiers for human exploration. There's no reason that we shouldn't have a significant number of people living and working on the moon, doing geological studies of asteroids and pioneering the path to Mars. The technology is well in hand.

You're not concerned about the dangers?

S: Of course I am, but danger is an integral part of true exploration. If you've ever been around aerospace vehicles, you know that a human being can get hurt in those big machines. Explorers 500 years ago faced a similar question: Is it too risky to sail to some unknown land in a rickety boat at the mercy of the wind? But look at what those daring explorations brought us in terms of the changes to the world. To be a great nation in the 21st century, the United States needs to explore the space frontier. If we choose this course, the road will be long and hard—and yes, dangerous. But so were the frontiers that this great nation took as previous challenges during the 18th, 19th, and 20th centuries. We should make a lasting commitment to the exploration of the moon and planets by *both* brave humans and sophisticated robots. We should inspire the world, and we should make history again. It's something America does extremely well.

If you could go anywhere in the solar system for one week, where would you go?

S: I'd like to spend a week exploring Neptune's giant moon, Triton. The Neptunian system is a scientist's playground. Triton seems to be geologically active like there's no tomorrow, even though it's only 40 degrees above absolute zero there. To conduct a field operation on Triton would be beyond my wildest imagination.

FROM THE APRIL 2006 ISSUE

Interview: Nobel Laureate Eric Kandel

Does psychotherapy work? We'd be a lot more certain if we slapped a little science on it.

By Susan Kruglinski | Sunday, April 02, 2006

dialogue-kandel

Eric McNatt

Neurobiologist Eric Kandel's early fascination with how the mind works led him into training as a psychiatrist interested in psychoanalysis. But in the 1960s he traded a therapist's sport jacket for a lab coat and began studying one of the slimiest creatures on Earth. At a time when brain researchers thought nothing could be learned from invertebrates, Kandel stunned the fledgling world of neuroscience by uncovering the mechanisms of memory in sea slugs, which earned him a Nobel Prize in 2000. He also coedited *Principles of Neural Science,* the book every medical student in America is required to read—all 1,414 pages of it.

In his new book, *In Search of Memory: The Emergence of a New Science of Mind,* Kandel examines the convergence of four critical fields—behaviorist psychology, cognitive psychology, neuroscience, and molecular biology. Still busy trying to coax more information out of sea slugs, Kandel also serves as a professor of biochemistry, physiology, and psychiatry at Columbia University, where his laboratory is located.

Your most recent lab work involves the potent emotion of fear. What have you learned?

We have identified some of the genes in the mouse that are important for both learned fear and instinctive fear. We've shown that by knocking out the stathmin gene, we can produce a mouse that is relatively fearless.

How does a fearless mouse behave?

Normally, when you put a mouse into an open field, it walks along the edge of the field, where the walls are—the mouse is in an enclosed chamber with walls around it—because it's afraid of being attacked by an intruder, and it makes occasional dashes into the center to make sure it's not missing some food or an interesting sexual partner. If you frighten a mouse, it stays in one corner and doesn't move at all. If you knock out this gene that is important for fear, the animal spends a lot of time in the center. It is no longer afraid.

Does the knockout shut down instinctual fear?

Yes, but it works on learned fear too.

Can you imagine using this research to benefit humans?

This gene could become a new target for antianxiety agents. We've also opened up the biology of happiness, showing that you can produce an animal that is more relaxed than normal, and this recruits activity in the pathways that are involved in positive reinforcement. That might open up a biology of security and comfort.

How do you study happiness?

In order to produce learned fear, you take a neutral stimulus like a tone, and you pair it with an electrical shock. Tone, shock. Tone, shock. So the animal learns that the tone is bad news. But you can also do the opposite—shock it at other times, but never when the tone comes on. Under those circumstances the tone indicates security and safety. We find that the animal acts as if it is content and secure, even more than it does without any shocks whatsoever. When we looked in the brain, we found that not only were the pathways that mediated fear turned off but also that happiness pathways were activated. The caudate nucleus, a part of the brain that mediates the effects of drugs that make you feel good, is lit up by this procedure.

So fear and happiness are part of the same system?

That's right, but I want to be clear that the knockout mice and the happiness procedure are not identical. They are different experiments. We showed that fear comes to a certain neural circuit and that there are genes that control that neural circuit, and you can turn that circuit on and off with specific genes. Period, end of paragraph. In a separate set of studies, we looked to see whether we can behaviorally—without manipulating genes—produce the opposite, and that is happiness. And that is how we got onto this paradigm. They may be related—it may be the same genes that shut off fear and turn on happiness, but we don't know that yet.

How is your research in memory related to fear and happiness?

Let's assume that you have a traumatic experience in childhood. Let's say you were sexually abused. You may or may not remember the cognitive components of it—the molester bothering you. But there are associated with the experience a series of autonomic and emotional changes that are implicit. And that component is learned fear. Seeing a strange person may therefore elicit in you a response that may be completely inappropriate—that strange person may have nothing to do with the molestation event, but somehow there are similarities that you recognize that bring this back. You learn emotional experiences as much as you learn cognitive experiences, except that they are more unconscious. Sometimes one represses the cognitive component of it, but it's often more difficult to repress the emotional component.

You have written that your training in psychotherapy influences your neurobiological work. Isn't there a split between psychotherapists and neurobiologists?

Yes, but I think it's a temporary one and perhaps an unnecessary one. I'm on an advisory board for the Ellison Medical Foundation, which is exploring whether one can use MRI brain imaging to evaluate the outcome of psychotherapy.

Haven't you questioned the value of psychoanalysis?

Early in my career, I was disappointed that psychoanalysis was not becoming more empirical, was not becoming more scientific. It was primarily concerned with individual patients. It wasn't trying to collect data from large groups of people who have been analyzed.

Will the Ellison project address this kind of problem?

What our study group is discussing is whether or not the time is ripe to use brain imaging to evaluate the outcome of psychotherapy. There are now two forms of psychotherapy that have been medically proven to be effective. One is cognitive behavioral therapy, developed by Aaron Beck at the University of Pennsylvania. The other is interpersonal therapy, which was developed by Myrna Weissman here at Columbia. Those are two scientifically validated forms of short-term therapy. In 20 sessions you can see improvements in mildly and moderately depressed patients. And there have been some preliminary studies with obsessive-compulsive neurosis where you can see a metabolic abnormality in the caudate nucleus in imaging. If you treat people with psychotherapy and they get better, that metabolic abnormality is reversed, which is the same thing that happens if you give them pharmacological treatment, like Prozac. So that's encouraging. We want to see whether there is a science here, whether or not the foundation should get interested in it. And people like Tom Insel, head of the National Institute of Mental Health, are going to participate as evaluators.

No one has ever conducted studies like this?

It has never been done systematically. We would like to consider doing it on a larger scale, maybe having several universities studying patients with different diagnostic categories to see how a controlled psychotherapy trial produces physical brain changes as a result of treatment.

Why has no one used imaging techniques to study psychotherapy before?

The field is very young. It's only recently that people got confident that psychotherapy under these circumstances works. The imaging methodology is relatively new, and the resolution is not that great yet. We need biological markers for each mental illness in order to see whether or not they can be reversed. So there are lots of technical problems. You know, our understanding of the mind is at a very early stage. These are the most difficult problems in all of biology.

Which illnesses might be considered for study?

Primarily obsessive-compulsive neurosis and anxiety disorders, such as post-traumatic stress disorders.

When did you first begin questioning psychotherapy?

I guess when I was at the National Institutes of Health, and when I came back into my psychiatric residency, which was in the 1960s. I was 30 years old. I was training as a psychiatrist. I had a personal analysis as part of my training. But it was not my personal analysis that caused me to question it. I actually benefited greatly from it. It was the fact that psychoanalysis as a discipline was not becoming scientific.

What do you think of psychotherapy these days?

Well, it is a little chaotic because there are lots of competing therapies out there. We might want to compare modes of therapy. I mean, who knows which is best? It's possible that you might benefit from one, and I might benefit from another. The different kinds of patients, different kinds of disorders, might be selectively treated by one kind of psychotherapy versus another. But that, I think, requires an independent standard for evaluation. And I think imaging might be one of the tools that provides that.

Do you think that some of the therapies are problematic?

I have no way of knowing that. I think it's problematic that people have not gone to the trouble to study this.

Has the psychology-neurobiology split hurt patients?

I think that psychopharmacological treatments have revolutionized psychiatry. On the other hand, I think anyone practicing psychiatry realizes that drug therapy is very effective but not perfect, that there are some patients who don't benefit from it, that there are some patients who benefit from drugs together with psychotherapy, and that in some cases psychotherapy by itself works. There was a time when psychoanalysts wanted nothing to do with biology, and biologists didn't want to touch psychoanalysis. That's changing. Now we need to have a systematic approach to the psychotherapeutic component of treatment, just as we have to the psychopharmacological aspects of treatment. That has not been done. What the Ellison Foundation and I are hoping to encourage is a more holistic approach to psychiatry, in which psychotherapy is put on as rigorous a level as psychopharmacology.

What does a psychotherapist need to know?

First, I think that people working in psychiatry should have a background in neuroscience, because psychiatry is in fact a form of clinical neuroscience. Second, that insofar as there are psychotherapies that are made available to patients, they should be shown to be effective. I am proposing a demanding criterion: that you be able to detect abnormalities in patients beforehand by such brain-imaging techniques as functional MRI [which measures blood flow in the brain], and then use imaging to see whether or not there is a change in those markers for the disease as the therapy progresses. Therapists need not necessarily use the insights of biology in their therapy, but they should be aware of what the indices are, have their patients imaged, and be able to follow the outcome.

Has any recent research in neuroscience surprised you?

Oh, my gosh, there are lots of things. For example, the study of decision making in the brain by people like Paul Glimcher is very interesting. William Newsome's work on the importance of value in decision making. Giacomo Rizzolatti's work on empathy, on how monkeys copy one another, is of profound significance. The work on smell by Richard Axel and Linda Buck is extremely interesting. I think the work on the molecular basis of sociological phenomena by Tom Insel and Cori Bargmann is very interesting. And Tom Jessell's work with neuronal networks is extraordinarily important. Sten Grillner's work on the workings of complex neurocircuitry is also of extreme importance. I would say the progress in understanding motor systems, the cognitive role in motor systems, is a brilliant advance and has revolutionized our understanding of how the nervous system is wired.

Does the research trickle down to therapists?

Yes. I would think that residents in psychiatry should be trained in neuroscience, like residents in neurology are. And this is happening. In fact, I see them as being sort of interrelated disciplines. I mean, the modes of therapy are different, and the character structure of the practitioners is different. But they are both treating the brain as an organ that is the target of disease.

But that isn't really happening, is it?

I don't think that's fair to say. Fields move slowly. It's happening. Nothing happens as fast as I would like it to. Even *Discover* magazine doesn't publish things as rapidly as I would like it to! [laughs]

What are the big unanswered questions in neuroscience?

I think we need to understand how sensory information is translated into action. We need to understand how unconscious mental processes develop. Where do they occur? What are the processing steps? What is the nature of decision making? Of free will? Can we get a vantage point on consciousness?

How close are we to understanding consciousness?

I think we have not made much empirical progress. But I think we have made a fair amount of conceptual progress. The work of Gerald Edelman and Antonio Damasio and of Christof Koch and Francis Crick has been influential in getting people to think about these problems in a useful way.

What do you think researchers will find consciousness to be?

Oh, my gosh. I have no guesses. I think it's a very deep problem, and I don't really have any original ideas about that.

FROM THE MAY 2006 ISSUE

Q&A: John McCarter

The head of Chicago's Field Museum lends a powerful new voice to the evolution debate.

By Kathy A. Svitil | Sunday, May 28, 2006

RELATED TAGS: HUMAN EVOLUTION

mccarter

Roy Zipstein

John McCarter is the chief executive officer and president of one of America's premier science research and exhibition centers: the Field Museum in Chicago. Under his leadership, the museum has embarked on a major expansion of its physical structure and the scope of its research activities. He oversees the work of 200 scientists, including far-flung legions of field researchers at the forefront of international efforts to protect endangered tropical environments, and home-based teams of laboratory investigators doing cutting-edge studies in new disciplines like molecular evolution. McCarter, who also serves as a trustee of the University of Chicago, has emerged as one of the leading critics of the intelligent design movement and an outspoken proponent of teaching modern evolutionary theory to all students. In March the Field Museum opened a controversial new exhibit called the Evolving Planet, which takes visitors on a 4-billion-year journey that shows life on Earth developing from single-celled organisms to dinosaurs and finally to humans.

Why did the museum create this exhibit?

The fundamental goal is to improve scientific literacy. We are concerned that middle schools and high schools are not doing justice to scientific curricula. There are lots of ways of getting at that goal. I'm very up-front about making our dinosaurs the marquee attraction of this exhibit. People love dinosaurs, and they are going to come to see them. But we want visitors to see the broader story of evolution, with dinosaurs in that evolutionary context.

Is the exhibit in response to the recent attention given creationism and intelligent design?

We've had an exhibit on evolution for many years, but as we went through it with children and teachers, we discovered that it was not having the impact we wanted. It was constructed in such a way that visitors rushed through to get to the dinosaurs, so we decided four years ago to change it. We think this will be a much more effective educational experience, telling a broader story. The intelligent design and creation controversies really came to the fore over the course of the last couple of years.

Is evolutionary theory losing ground?

No. It is being strengthened every day. We have ongoing bio-geography studies in the Philippines that look at live animals to see how the complexity of island populations evolves. We are getting a grasp on geologic forces like plate tectonics and how continents and mountains rise and form. We are able to look at contemporary living species and infer from the molecular diversity how those organisms evolved over time. Evolution is the base of much that goes on in health care. I don't think evolution is losing ground at all.

Are you frustrated by the attention intelligent design is getting?

I'm disappointed. I think it underscores the importance of the educational mission of institutions like this. It adds responsibility. Unlike a young teacher who has just finished his or her master's degree in education with an undergraduate degree in science, we can't be intimidated by a 55-year-old school board member who says "Don't teach evolution" or who wants to teach it in parallel with other so-called theories.

Why do you think anyone listens to the people pushing intelligent design as an alternative to evolutionary theory?

I think we are going through a period of time where faith-based institutions are becoming more powerful in people's lives. It tracks with the political climate. It is the theological dimension of an upwelling of conservative enthusiasm in this country.

Do you think that upwelling will grow in strength?

That is hard to predict, but the pendulum swings back and forth. I think that five years from now, creationism as a theology will still be powerful, but this intelligent design tactic, which is supported by a very small group of people, will be history.

Is the public embracing these ideas because they don't understand what science is?

Yes, absolutely. I think that kids get turned off to science at some point—fifth grade, sixth grade, seventh grade—when science is perceived as too hard and too complicated. I've traveled to China and visited universities where students are triple-bunked and start school at seven in the morning. They are studying computer sciences, mathematics. They are studying hard scientific subjects. That does not happen here, and I think we disadvantage ourselves as a country and as a society if we fail to capture the imagination of kids when they are 10 to 15 years old and enable them to direct themselves in scientific pursuit.

Even if the museum can reach these kids, aren't they likely to go home and get a different view?

You can counteract that by telling stories. We try to make the museum experience telling enough that it becomes a conversation with families over the dinner table two nights later. There is no hubris in this. We realize that we are a very limited part of the world. There are magazines, television, a proliferation of cable channels. There is a lot of competition for time, from playing Little League baseball to computer games. We know we are a very small part of a family's or an individual's experience. There are polls showing that half the U.S. population accepts the theory of evolution. But 75 percent of the people who come here do. You could say that we are preaching to the choir or, more positively stated, that we are reinforcing their understanding of evolution and building their confidence with fact and effective storytelling. They can say, yes, this is something that I can see evidence for in the fossil record. And for those people who don't accept it, the exhibit may enable the families to have a discussion about what their 15-year-old saw and how that fits into the overall faith of the family. We are not against religion. We are very supportive of religions and religious institutions. Much of this museum is a celebration of the impact of religion on cultures. But we do that in anthropology. We don't do that in paleontology.

What's the danger in meshing science and religion?

Where we get in trouble as a society is when people of one persuasion or one capability jump into another field —when theologians come into science and attempt to reinterpret scientific records through supernatural intervention, and alternatively, when scientists go into theology and say "There is no God." It is really not the business of either. There should be a common dialogue, a middle ground where people can discuss issues like this as matters of philosophy as well as matters of theology and matters of science. We've lost a lot of that public discourse as we've moved to this frenetic, fast-paced life, with no time for reflection and discussion and debate.

Is it wrong for people to want their universe to make some kind of sense, in all its facets—to want to make it orderly?

I think people want to simplify, because everyone is so busy. We have moved from a society with the traditional family of four, with Mom at home and the father working, to dual-career families, and we have the complexity of raising children at the same time. There is a real desire to simplify. People don't have the time to reflect on what is going on in the world. Look at this polarization of attitudes toward the war in Iraq. There is a much more complicated set of issues concerning how Iraq fits into global strategies, but there is no time for a public discourse about those larger issues. Look at Ted Koppel on ABC's Nightline. He would present a very thoughtful analysis of these larger issues, but two comedians with light talk on CBS and NBC had 80 percent of the market in that time slot. Same thing with National Public Radio. It may be part of your life, and of my life, yet only 2 percent of the population is listening to NPR. I think institutions like this don't have a crack at people's attention and time, so you have to be really good at delivering messages or explaining controversies in a way that sticks in people's minds.

Does promoting a particular point of view go against the traditional role of a museum as a collection of objects?

At the core is the collection, but based on that collection is all the science that we do. That fish [McCarter points to a large fossilized fish in his office] is a beautiful object; it is fascinating to look at, but in and of itself, it is not that important. Where it becomes important is in the story of what happened 50 million years ago in Wyoming, in the Green River Formation, where this fish once existed. The fossil helps us interpret what was going on there geologically, how evolution has taken place to lead to contemporary living things. So collections are important only to the extent that you are able to interpret them scientifically.

Should museums make their holdings more freely available to the public? Does the public have a fundamental right of access to the information?

When I started here nine years ago, I was warned not to build a Web site. People said that if the images were available online, no one would come to the museum. But I think that's wrong. I think it stimulates physical attendance. We are trying to make our collections more broadly accessible. Right now, we are slowly making digital reproductions of the 23,000,000 specimens in our collection. Eventually, we will have a lot of those images on our Web site, so that people in Peru or in Kenya will be able to share these collections.

It seems museums have switched from being repositories of artifacts and information and history to being advocates for a specific viewpoint.

I don't think I'd call it advocacy. Again, I call it storytelling. For example, when we open our Pre-Columbian America exhibit in 2007, we will focus on a wonderful collection of artifacts that traditionally were displayed in cases—the beadwork of the Plains or Woodland Indians, or the Maya or the Toltecs. You would see an object, but there was no contextual story around that object. What we are doing now is using the artifacts to tell a story, from people coming over the Bering Land Bridge at the time of the Ice Age, through the peopling of hunter-gatherer societies, to the development of agriculture and complex urban societies.

Aren't you communicating a particular message with that story?

Yes, a point of view. For example, we are telling the story of the land bridge, but we are also telling these cultures' creation stories: "We have always been here . . . we came from the sky . . . we came from the ground." We respect their traditions.

But you don't respect Western religious traditions in the same way in the evolution exhibit.

No, we don't, and maybe that is inconsistent. Western religions have their own fascinating traditions. We have brought exhibits such as The Dead Sea Scrolls and Heaven on Earth: Orthodox Treasures From Siberia and North America, thereby sharing important dimensions of Western religions with our visitors.

What is the harm in telling the other story?

I don't think there is any harm, as long as it is not posed as a scientific alternative to the story of evolution. Many of my colleagues here and many scientists around the country are people of faith. It is not an either/or issue. Rather than saying that something like the human eye is too complicated to understand, so a supernatural intrusion must have enabled it, we are saying that it is possible because of a scientific theory that has been under development for 150 years and has been reinforced by the fossil record and now by the molecular record. Trilobite eyes will be an important part of the exhibit because in them you start to see the development of vision. You see the ability to discriminate between light and dark, and then the capability to pinpoint direction through vision. Ultimately, after hundreds of millions of years of evolution, the primate eye comes about. Once you understand that context, the history of how vision developed, you don't need to bring the intrusion of an intelligent designer into the process.

Do you really believe trilobite eyes can change someone's opinion about the hand of an intelligent designer?

Sure. The mainstream theological community is already way beyond the literal interpretation of the biblical accounts of Adam and Eve and the Garden of Eden and seven days of creation. Instead, they are saying that those are wonderful stories, created 2,000 years ago by people who were trying to explain their world, not that they are scientific fact. To me, the important issues of theology are the applied morality of behavior and guidance, rather than that this whole thing took place in seven days. That's an example of the simplification: Give me easy answers, simple stories, rather than challenging me with very tough issues. Stem cells—that's a tough issue. Abortion—that's a tough issue. That's where we should be focusing our attention.

WEB EXCLUSIVE

Infectious Defense: How to Prepare for Biological Warfare

Biowarfare expert David R. Franz on the real risk of bioterrorism, Saddam Hussein's non-existent WMDs, and how HIV/AIDS might prevent us from eliminating the next smallpox.

By Kathy Svitil | Wednesday, June 14, 2006

RELATED TAGS: WEAPONS & SECURITY

In the fall of 2001, five people died after exposure to weapons-grade spores of the *Bacillus anthracis* bacterium—anthrax—delivered in postal letters. The crime, which remains unsolved, brought national and international attention to the looming danger of bioterrorism and biological warfare.

Future bioterror attacks may be unavoidable, says retired United States Army Colonel David R. Franz, who has spent more than 25 years studying—and preparing medical countermeasures against—biological warfare and bioterrorism. Franz, who worked as a veterinarian before earning a doctorate in physiology, is currently the vice president and chief biological scientist at the Midwest Research Institute. He is the also the first director of the National Agricultural Biosecurity Center. In the late 1990s, Franz served as the chief inspector on three biological warfare inspections to Iraq for the United Nations Special Commission.

During your inspections of Iraq, you found bioweapons.

DF: We did. In that era, 1998, we found them. I don't think it was a high-quality program.

Were you surprised bioweapons weren't found in the recent inspections?

DF: No. Right before we went in the second time, I was on record for both MSNBC and CNN saying that I won't be at all shocked if we don't find biological weapons this time.

It sounds like I had a lot of wisdom, but in my next breath, on MSNBC and CNN, I said that we will absolutely find chemical weapons.

Why hasn't a biological terrorism attack happened?

DF: The hardest question I am asked is why it hasn't happened. It is not necessarily as easy as everyone says. When you work through all the possible scenarios, you find technical difficulties for the bad guys, fortunately. That is why, I think, I'm less concerned about it than [the average person] who just knows that bad things can happen with biology.

I think of a spectrum of technical barriers. On the very low end, something like foot-and-mouth disease in cattle... On the far end of the spectrum there are the classical agents—anthrax, plague, tularemia. There are significant technical issues there.

Why hasn't an attack at the lowest level occurred? That's a behavioral issue, not a technical issue. It is one of intent, it seems to me. And, for some reason it hasn't been done.

Can't we just develop sensors that will detect an attack—anthrax in the air?

DF: If we had that, we might not need to think about vaccines. We would all have a little thing in our pocket or our purse that we could put on to protect our airways. But, I don't think we are going to get there. Biological detectors are complicated. You need antibodies to the bugs, or PCR primers, and the detectors take a lot of care and feeding.

Is there a relationship between emerging disease and bioterror?

DF: Not everyone agrees with me, but I use a very simple equation to think about it: bioterrorism equals emerging infectious disease plus intent.

Could we stop a would-be terrorist if they were intent on causing harm?

DF: I think it would be really tough. If we do, it would likely be through something we pick up in intelligence. We hear something is planned, or someone has this little laboratory in their basement or in a cave somewhere, or we have a scientific colleague, somewhere in the world, working with someone who hears something.

Assuming you can't stop it, then what?

DF: I looked at the bugs and said that for medical countermeasures we can't make a "1-to-N" list and say we are going to go down the list and make a vaccine for each one—there are just too many. So I looked at the [dangerous] outliers.

We now have enough vaccine for smallpox to immunize the population. We have vaccines now for anthrax and antibiotics for anthrax, and we have some stockpiles and a lot of other preparations for foot-and-mouth disease.

Then under that, where we can't afford to do specific countermeasures, I like surveillance, general diagnostics. It is a lot easier to get diagnostics through the FDA. Anything you have to stick into people or that people take orally, there are a lot more hoops to jump through.

And then under that a strong biotechnology and basic bioresearch infrastructure. In the future, I think we'll come up with more generic countermeasures that may boost our immune system a little bit.

How far in the future?

DF: I always say 30 years.

Over the long haul, aren't you going to drive the evolution of the bugs toward being craftier, more resistant?

DF: Probably, to some degree. It depends on the bug.

Is there anything else we can do?

DF: There is no perfect solution. We can't stop a bioterrorist. We might stop some with deterrence, and if it occurs we have these generic countermeasures and a good public-health system, and then for what that can't deal with we need to have our people resilient.

What do you mean by that? Accept that it's going to happen, and just deal with it?

DF: Sort of. Not ever accept terrorism—we're going to do everything we can do to fight this—but be able to deal with it, more mentally than any other way.

I don't think the public would be ready to hear that message. They want to hear that it is not going to happen, and that they're protected if it does.

DF: I think of two examples. One is Israel. They've become a more resilient society. But it isn't by chance. They've focused on education, on understanding terrorism.

And then I remember a snippet of the news I saw after Katrina on the Cajun families out in the rural areas. They just got their boats, their shotguns, checked on their neighbors. They are used to living off the land, and have a close-knit social structure. Those kinds of things can make a great difference. I consider that resilience as well.

Has anyone calculated the odds that an individual person will ever be attacked by a bioterrorist?

DF: You're more likely to be hit by a truck. We lose 440,000 people to smoking related illnesses every year… We lose 20-80,000 people to influenza every year, 120,000 people to automobile accidents. We lose five people to bioterrorism.

I'm sure you know where I'm going: Why spend money on this, which might not ever happen, instead of on these known things?

DF: One reason is that we're willing to let our fellow citizens die if they know it is going to take a long time and they kind of enjoy what leads up to it. Like smoking. We are willing to let people die of influenza if they are old and their immune systems aren't very good and they are probably going to die soon anyway. We are not wiling to have even a very low risk of dying if someone intentionally does it. We can do it to ourselves, but nobody can do it to us.

If you were an ingenious bioterrorist, wouldn't you work on some unexpected, not-so dangerous organism, and make it worse?

DF: The bad news is biology is very squishy; the good news is biology is very squishy. For those of us interested in countermeasures, you think you've got a vaccine nailed, or you think you have the perfect antiviral drug – then you find out it is toxic, or the vaccine protects mice but not primates. Fortunately the same holds true for the person who would use biology against us. You can get a group of experts, molecular biologists, virologists, together in a room and they say "I can do this" but you get in a lab and it is not as easy as in the conference room.

What are you most worried about?

DF: I am probably most concerned about the highly contagious human agents—influenza, smallpox—which could have a huge impact on this world, because the world is smaller and we have HIV/AIDS today.

Why does that matter?

DF: I don't think we would ever eradicate smallpox again, because you couldn't immunize AIDS patients or maybe even HIV patients [because they would be vulnerable to the virus in the vaccine].

The other thing that I worry about a concept called "reload." Say you have two kilos of high-quality, powdered anthrax in ten American cities. It might not be totally efficient but can infect a lot of people. Then you say 'in two weeks, I'm going to do the next city and I won't tell you what it is,' then you do the next city. That is feasible, and would be very hard to deal with.

Because of the injuries or the psychological damage?

DF: If they said 'it's going to be Detroit next,' you could deal with it. If they didn't say [where], it would have a real psychological impact. Would you want to go downtown or anywhere if you knew that there were 10,000 people suffering from inhalational anthrax and a lot of them would die?

If anything is scary to me, it is the contagious agents, because an outbreak can start with such a small group of people and just... go.

DF: I think we would change our lifestyles very quickly. We would probably travel a lot less, we would probably wear masks when we go to the grocery store, we would probably wash our hands a lot more.

How much should we worry about agricultural bioterrorism?

DF: The ag threats fall below the threshold that we might compare to large natural disaster. But foot-and-mouth disease is one I worry about because it could devastate our economy. Foot-and-mouth could take us into tens of billions of dollars of economic damage.

If you rewrite history and the 9-11 attacks never happened, would anyone have thought it likely that planes would be hijacked and crashed into targets? So isn't it possible that future attacks will be things you're not looking for?

DF: Go back to my equation that bioterrorism is emerging infectious disease plus intent. We have a good medical infrastructure and public health infrastructure looking for emerging infectious disease. So I think we're in better shape with regard to biology than we are to the next terror event—someone flying airplanes into bridges, those off-the-wall kinds of things.

FROM THE JUNE 2006 ISSUE

Discover Interview: E.O. Wilson

Biology's chief provocateur explores the evolutionary origins of cooperation, warfare, and the tribal mind.

By Richard Conniff | Sunday, June 25, 2006

Gerald Forster

Edward O. Wilson has spent a lifetime squinting at ants and has come away with some of the biggest ideas in evolutionary biology since Darwin. *Sociobiology* and *biodiversity* are among the terms he popularized, as is *evolutionary biology* itself.

He has been in the thick of at least two nasty scientific brawls. In the 1950s, his field of systematics, the traditional science of identifying and classifying species based on their anatomies, was being shoved aside by molecular biology, which focused on genetics. His Harvard University colleague James Watson, codiscoverer of the structure of DNA, declined to acknowledge Wilson when they passed in the hall. Then in the 1970s, when Wilson published *Sociobiology: The New Synthesis,* other Harvard colleagues attacked the idea of analyzing human behavior from an evolutionary perspective as sexist, racist, or worse. He bore all the hostility in the polite, courtly style of his Southern upbringing, and largely prevailed. Sociobiology, though still controversial, has become mainstream as evolutionary psychology. The molecular biology wars may also be ending in a rapprochement, he says, as the "test tube jockeys" belatedly recognize that they need the "stamp collector" systematists after all.

Wilson, who turns 77 this month, has published three books during the past year that fit his own wry definition of a magnum opus: "a book which when dropped from a three-story building is big enough to kill a man." *Nature Revealed* (Johns Hopkins) is a selection of his writings since 1949. *From So Simple a Beginning* (W. W. Norton) is an anthology of writings by Darwin, and *Pheidole in the New World* (Harvard) is a reorganization of an entire ant genus, including 341 new species Wilson discovered and more than 600 of his own drawings.

You once wrote that you saw yourself parading provocative ideas "like a subaltern riding the regimental colors along the enemy line."

That's right, "along the enemy line." That's an adolescent and very Southern way of putting it, but I wanted to say that I'm a risk taker at heart.

And a provocateur?

Yes, but not a controversialist. There's a distinction. Once I feel I'm right, I have enjoyed provoking.

Your adversaries from the 1970s would be appalled by how much your ideas about sociobiology have taken hold.

The opposition has mostly fallen silent. Anyway, it was promoted by what turned out to be a very small number of biologists with a 1960s political agenda. Most of the opposition came from the social sciences, where it was visceral and almost universal.

The social scientists were threatened by the invasion of their territory?

That's right.

The same way that you were threatened by the molecular biologists invading the biological field in the 1950s?

They didn't invade it so much as they dismissed it. What's been gratifying is to live long enough to see molecular biology and evolutionary biology growing toward each other and uniting in research efforts. It's personally satisfying and symbolic that Jim Watson and I now get on so well. We even appeared onstage a couple of times together during the 50th anniversary year of the discovery of DNA.

You once described Watson as "the most unpleasant human being" you'd ever met.

He was, in the 1950s. But recently we were on the *Charlie Rose* show together, talking about evolution and biology and Darwin, back and forth with a remarkable degree of harmony between the two of us. I've always admired him greatly, then and now.

How do you see the two fields—evolutionary biology and molecular biology—collaborating?

Intimately, in a number of ways. The molecular biologists base family trees on DNA sequences, and it often requires only a relatively small amount of a genome to say with a high level of confidence which species are closest to one another—that is, which species branched away from each other in evolution most recently. So the tree of life is adding a lot of detail, and it's also getting a time line. That's one area nonetheless where evolutionary biologists are essential from the start, because the molecular biologists don't know the species. But where molecular biology is really taking off on its own is in the exploration of microbial life—bacteria, archaea, and microscopic fungi. These are huge classes of species that can't be reliably distinguished by ordinary visual examination of body parts. But it's possible to sequence a complete bacterial genome in as little as four hours. It's been estimated that as many as 4 million species of bacteria occur in a ton of soil, just a few scoops of a backhoe. The point is that we're opening the diversity of life at this most basic level. It's going to be full of surprises.

Surprises that will make a difference?

Oh, yes. Just to understand how all these organisms operate in ecosystems will have an enormous impact. Consider the role of nematode worms in maintaining the health and fertility of soils. We don't know how many nematode species there are. We don't know what they're doing. We do know they must be important. Consider this: Four out of every five animals on Earth are nematode worms. What are we to make of that immense biomass about which we understand next to nothing?

But we're starting to understand it using molecular analysis?

I don't want to give my molecular colleagues too much credit. The genomics approach to identifying nematodes and bacteria is a major breakthrough. They can put names on genomes: "Well, we know X-105BH2 has been found here." But what does the organism look like? What is its anatomy? Its metabolism? There has to be a uniting of molecular and systematic biology. One deficit caused by the molecular revolution is that we don't have experts working on all these various groups, on their natural history, their ecology, their behavior. We don't have the wherewithal to map the biodiversity of the Earth, or even the United States. The systematists, of which I'm one, have built up a very large body of knowledge, and the genomicists are living off that capital. But they are soon going to run out.

Let's talk about your idea for an encyclopedia of life.

Thanks to the Internet and to advances in digital photography, we have the ability to put online superb images of even the smallest organisms. So we can speed up the mapping of world biodiversity by an order of magnitude easily. What we need is an electronic encyclopedia of life, with one page for each species. On each page is given everything known about that species. This should be the driving force for future biodiversity studies; it's as simple as that.

But it's not happening?

The responses I've gotten are so positive, including from molecular biologists, that logic tells me this is about to take off. They want to know what's out there. Once there's an encyclopedia of life that they can browse, they will enjoy an almost infinite treasury of important projects to work on. Suppose there's a snail in Indonesia that produces a powerful fungicide. Well, that might be known by just one elderly guy at Idaho State University who's a specialist on the snails of Indonesia. But when that species is in the encyclopedia, you can type in "powerful fungicides," "snails," "tropical Asia" and . . .

And there it is.

You got it. That's my dream.

One of your other dreams is to see evolutionary biology and the humanities come closer together. How?

I'm looking for a congenial meeting. A lot of the suspicion from the social sciences and humanities side is fading, and there are young people coming in who are eager to get what they can from the natural sciences. They don't feel threatened; they see this as a resource.

In the popular mind, the word *Darwinian* still often means conflict—fighting over resources—whereas the reality is often adaptation by cooperation.

That's why I wrote the book *Sociobiology,* about the adaptive value of cooperative behaviors. I wrote a paper with Bert Hölldobler last September that proposes a controversial new model of the origin of social behavior, including cooperative behavior in the insects.

Controversial in what way?

I'm taking the idea of kin selection, and I've critiqued it. Kin selection is the idea that cooperation arises, especially in the eusocial insects—bees, wasps, ants, termites—because of individuals favoring collateral kin: not just Mom and Dad or your offspring but, just as important, brother, sister, cousin, and so on.

So you cooperate with close kin because it helps get some of your shared genetic heritage into future generations.

I found myself moving away from the position I'd taken 30 years ago, which has become the standard theory. What I've done is to say that maybe collateral kin selection is not so important. These ants and termites in the early stages of evolution—they can't recognize kin like that. There's very little evidence that they're determining who's a brother, a sister, a cousin, and so on. They're not acting to favor collateral kin. The new view that I'm proposing is that it was group selection all along, an idea first roughly formulated by Darwin.

The notion of group selection is heresy, is it not, in the current thinking about evolution?

Yes. I'm being provocative again, because this is a radical departure.

The theory is that natural selection works only on individuals, not the social group. Isn't that the idea of the selfish gene?

No, that's where a lot of biologists mix things up. The *unit* of selection is a gene, the basic element of heredity. The *target* of selection is normally the individual who carries an ensemble of genes of certain kinds. But the target can also be the group. How well does that group survive vis-à-vis other groups and vis-à-vis solitary individuals of the same species, and how well does that group produce its own kind? For group selection to happen, all you need is one gene that would cause individuals to come together, and for some of them to be willing to be subordinated and become workers.

But ant workers give up their reproductive futures. Why would they do that, from a Darwinian perspective?

That is easy to explain by a feature that we now recognize as universal: the plasticity of expression of single genes. The same gene can produce different body types depending on environmental conditions. The classic case is the arrowleaf plant. If grown on dry ground, it produces an elephant-ear leaf; if grown in a pond, it puts up leaves like lily pads; and if grown in deeper water, it grows up with slender leaves like eelgrass.

So consider a gene that has plasticity such that in one setting an individual carrying that gene becomes reproductive. Maybe this individual was the ant or wasp that arrived first, maybe it was the biggest one, or maybe it was the one to just by accident start laying eggs first. The important thing is that the reproductive role can shift from one colony to the next and from one generation to the next. The group forms, and some individuals by circumstance become workers. Their cooperative behavior and the division of labor confer superiority on that group, with that particular gene, over other groups. It could be as simple as that.

So why isn't it more common?

It only occurs if the environment is extraordinary in some way, producing a resource that is very valuable—like a hollow stem that might serve as a nest site—so that it pays a group with social organization to defend and exploit it. Otherwise, altruism toward fellow group members is discouraged by the Darwinian advantage of surviving and having personal offspring. But once the ants and termites jumped the high barrier that prevents the vast variety of evolving animal groups from becoming fully social, they dominated the world.

Is group selection also why humans are now so dominant?

What I've done is pose the question. For social insects, I'm presenting as much evidence as I can summon for each of the two opposing views: Either collateral kin selection is the key, or group selection favored by very unusual environments caused them to be altruistic. And I'm pretty sure I'll continue saying, "I think it's the latter." But if you think it's the former, let's see better evidence.

For humans this would mean that the tribe was the most important factor in our evolution.

Darwin pretty clearly says in *The Descent of Man* that it's tribe against tribe—exactly what I'm saying. If this turns out to be the case in the early origin of social behavior in human beings, it might be the best explanation of endemic warfare, which humanity has engaged in since prehistory.

And of endemic altruism?

Yes, precisely. The genes that favor this type of group cohesion would also favor an innate sense of morality and group loyalty. It would explain how so often group or tribe loyalty overrides even family loyalty. It would help to explain why, for example, it is the squad or the platoon that men fight and die for, more even than country or religion. So I'm going to be spending time in the future looking into this area, with human behavior as a special case.

Has anyone attacked the idea?

No, because I've kept it to social insects. But I have respected colleagues working on social insects who think I got it wrong. Right now it's a work in progress and a trial run.

So you're not yet riding the flag along the enemy lines?

No, I'm not. Not for humans anyway. I might in a couple of years.

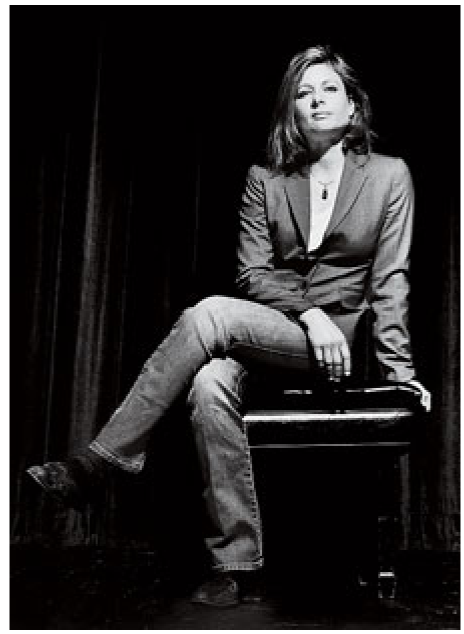
FROM THE JULY 2006 ISSUE

The Discover Interview: Lisa Randall

One of physics' brightest stars ventures into 10 dimensions, visits other universes, explains gravity, and keeps her sense of humor.

By Corey S. Powell | Saturday, July 29, 2006

RELATED TAGS: STRING THEORY


Phil Knott

Lisa Randall laughs. That may not seem at all remarkable until you consider what's on her mind right now. She is out to liberate humanity from the pervasive but quite possibly mistaken assumption that we live in a three-dimensional world. "The disinformation campaign began in the crib, which first introduced you to three spatial dimensions," she warns in her recent book, *Warped Passages: Unraveling the Mysteries of the Universe's Hidden Dimensions* (Ecco, 2005).

Starting in earnest a couple of decades ago, a group of physicists began seeking deeper truth in string theory, which holds that the fundamental particles of nature consist of minuscule vibrating strands of energy. Problem is, the theory works well only if the strings vibrate in more than three dimensions. Randall, a theoretical physicist at Harvard University, is a leading light of a second generation of researchers who are taking that idea to an even grander level, envisioning not just tiny strands but huge territories of higher dimension, called branes. She thinks this approach could revolutionize our understanding of gravity and uncork the deepest workings of the universe.

Yet Randall is resolutely down to earth. She chafes at the thought that her ideas should be restricted to the confines of academia, she both respects and swats aside her importance as a woman in a male-dominated field—and then there is that laugh, hearty and throaty, that erupts repeatedly during our conversation. She finds this world rich and comforting and funny. She just wants to give it a little more dimension.

Where did your interest in physics begin?

When I was in school I liked math because all the problems had answers. Everything else seemed very subjective. The teachers in English class would say, "What is the reason that this is an important book?" They'd look for the three good reasons, whereas you might think of some other one. I didn't like the arbitrariness of that. Later I decided that just doing math would drive me crazy. I'd be up all night working on a problem, and I thought, "I can't live the rest of my life like this." [Laughs] I wanted something more connected to the world.

Speaking of staying connected to the world—in your work you imagine extra dimensions, but you still have to live on the same planet as the rest of us. Do you carry around the image of other dimensions in your mind?

It's momentary. In my book I describe a time walking over the Charles River and thinking, "You know, I really do believe there are extra dimensions out there." Sometimes I have a sense of what I'm seeing being a small fraction of what's there. Not always there, but probably more often than I realize. Something will come up, and I'll realize I'm thinking about the world a little differently than my friends.

So you intuitively believe higher dimensions really exist?

I don't see why they shouldn't. In the history of physics, every time we've looked beyond the scales and energies we were familiar with, we've found things that we wouldn't have thought were there. You look inside the atom and eventually you discover quarks. Who would have thought that? It's hubris to think that the way we see things is everything there is.

If there are more than three dimensions out there, how does that change our picture of the universe?

What I'm studying is branes, membranelike objects in higher-dimensional space. Particles could be stuck to a three-dimensional brane, sort of like things could be stuck to the two-dimensional surface of a shower curtain in our three-dimensional space. Maybe electromagnetism spreads out only over three dimensions because it's trapped on a three-dimensional brane. It could be that everything we know is stuck on a brane, except for gravity.

Yet we very clearly see only three dimensions when we look around. Where could the other dimensions be hiding?

The old answer was that the extra dimensions were tiny: If something is sufficiently small, you just don't experience it. That's the way things stood until the 1990s, when Raman Sundrum and I realized you could have an infinite extra dimension if space-time is warped. Then with Andreas Karch, I found something even more dramatic—that we could live in a pocket of three dimensions in a higher-dimensional universe. It could be that where we are it looks as if there's only three dimensions in space, but elsewhere it looks like there's four or even more dimensions in space.

And there could be a whole other universe set up that way?

Possibly. It would be a different universe because, for example, bound orbits [like Earth's path around the sun] work only in three dimensions of space. And the other universe could have different laws of physics. For example, they could have a completely different force that we are immune to. We don't experience that force, and they don't experience, say, electromagnetism. So it could be that we're made of quarks and electrons, while they're made up of totally different stuff. It could be a completely different chemistry, different forces—except for gravity, which we believe would be shared.

What is so special about gravity?

In string theory there are two types of strings, open ones with ends and closed ones that loop around. Open strings are anchored to the surface of a brane, so the particles associated with them are stuck on the brane. If you have an open string associated with the electron, for example, it's on a brane. Gravity is associated with a closed string. It has no end, and there is no mechanism for confining it to a brane. Gravity can spread out anywhere, so it really is different. It can leak out a little into extra dimensions. That can explain why gravity is so weak compared with the other forces. After all, a little magnet can lift a paper clip against the pull of the entire Earth.

Some of these ideas sound, frankly, a bit crazy to the average person. Where do they come from?

One reason people think about extra dimensions is string theory, the hypothesis that fundamental particles are actually oscillations of tiny strands of energy. String theory gives you a way to combine two very different models of the world, quantum mechanics and general relativity. Basically, quantum mechanics applies on atomic scales, and general relativity applies on big scales. We believe there should be a single theory that works over all regimes. String theory does that, but only in a universe that has more than three dimensions of space. More generally, there's stuff we don't understand if there are only three dimensions of space, and some of those questions seem to have answers if there are extra dimensions. Also, no fundamental physical theory singles out three dimensions of space. The theory of gravity allows any number. So it's logical to think what the world would look like if extra dimensions are there.

How will we know if your ideas are right?

Experimentalists will look for what are called Kaluza-Klein particles, which are associated with the hidden dimensions. The Large Hadron Collider [a particle accelerator on the French-Swiss border that will switch on in 2007] could have enough energy to produce these particles. In our theory, Kaluza-Klein particles will decay in the detector—you find the decayed product and you can reconstruct what was there. That would provide very strong evidence of extra dimensions. Maybe within five years we'll know the answers.

These are costly experiments. Do you worry about the public's willingness to support such purely theoretical research?

I'm really concerned about it. If we don't do it now, we'll probably never do it. We've built up the technology; we're at a point where if we don't continue, we'll lose that expertise, and we'll have to start all over again. True, it's expensive, but at the end of the day I believe it will be worth it. It makes a difference in terms of who we are, what we think, how we view the world. These are the kinds of things that get people excited about science, so you have a more educated public.

One of the amazing things about your work is that so much of it comes straight from your imagination, not from rooting around in the laboratory. It seems very much like chalk-and-blackboard research.

Right, the blackboard. Those are the things that seem to strike people, that we have blackboards with equations all over them and that we are talking to each other a lot; we're not just going into our offices and ignoring the rest of the word. But we do just go and think sometimes. Once you're really focused, if you get jogged out of it, you have to go back and really reestablish that. It's like Fred Flintstone and his bowling ball: You don't want to interrupt someone when they're in that state. Then again, sometimes we're just talking and writing together on a piece of paper, and sometimes we're at that blackboard putting ideas back and forth. Our work is all those things. It's reading what other people have done, trying to puzzle through something, getting stuck, getting unstuck, trying to find different ways around a problem.

You don't exactly fit the image of the graying, tweedy professor. Does being a young woman in a male-dominated field carry special responsibilities?

If only I was still young! [Laughs] I thought maybe I'd make it all the way through an interview without having to talk about this. But, yeah, I think it does. I'm probably more careful, and probably I spend more time on this particular issue. Also, in writing my book, I felt it had better be good, because there aren't that many women in the field, and I thought it would be subject to extra scrutiny. So there is extra responsibility; the flip side is that potentially there's extra reward if it draws a more diverse group into physics.

Outside your own area of research, where do you see the most vibrant things happening in science today?

Neuroscience is exciting. Understanding how thoughts work, how connections are made, how the memory works, how we process information, how information is stored—it's all fascinating. Experimentally, though, we're still rather limited in what we can do. I don't even know what consciousness is. I'd like someone to define consciousness.

Many people would say physics has a long way to go too. Does it bother you that the things you're excited about now may seem quaint as soon as someone comes up with a better theory?

True, we haven't found all the answers, but we've found some and we're finding more. The fact that we don't know everything doesn't mean we know nothing. People have asked me, "Why bother, if you don't get final answers?" I said, "If someone gave me a dessert, and I knew it wasn't the best dessert ever, I would still be really happy to eat it and wait for the next one."

Will physics ever be able to tackle the biggest questions—for instance, why does the universe even bother to exist?

Science is not religion. We're not going to be able to answer the "why" questions. But when you put together all of what we know about the universe, it fits together amazingly well. The fact that inflationary theory [the current model of the Big Bang] can be tested by looking at the cosmic microwave background is remarkable to me. That's not to say we can't go further. I'd like to ask: Do we live in a pocket of three-dimensional space and time? We're asking how this universe began, but maybe we should be asking how a larger, 10-dimensional universe began and how we got here from there.

This sounds like your formula for keeping science and religion from fighting with each other.

A lot of scientists take the Stephen Jay Gould approach: Religion asks questions about morals, whereas science just asks questions about the natural world. But when people try to use religion to address the natural world, science pushes back on it, and religion has to accommodate the results. Beliefs can be permanent, but beliefs can also be flexible. Personally, if I find out my belief is wrong, I change my mind. I think that's a good way to live.

So does your science leave space for untestable faith? Do you believe in God?

There's room there, and it could go either way. Faith just doesn't have anything to do with what I'm doing as a scientist. It's nice if you can believe in God, because then you see more of a purpose in things. Even if you don't, though, it doesn't mean that there's no purpose. It doesn't mean that there's no goodness. I think that there's a virtue in being good in and of itself.

I think that one can work with the world we have. So I probably don't believe in God. I think it's a problem that people are considered immoral if they're not religious. That's just not true. This might earn me some enemies, but in some ways they may be even more moral. If you do something for a religious reason, you do it because you'll be rewarded in an afterlife or in this world. That's not quite as good as something you do for purely generous reasons.

FROM THE AUGUST 2006 ISSUE

Discover Interview: Will Wright

The master of the computer god game tackles alien life and dreams up a world that would make Darwin drool.

By Alan Burdick | Tuesday, August 01, 2006

RELATED TAGS: COMPUTERS

Dan Chavkin

Will Wright followed a typically eccentric path into computer-game design: some college classes in computer science and architecture, a few homemade robots, no university degree. A deep interest in science, however, infuses all his creations. *SimAnt,* in which players try to corral an ant colony into conquering a suburban home, was modeled on the insights of ant expert Edward O. Wilson. For *SimEarth,* a global-ecosystem game, Wright consulted with biologist James Lovelock, originator of the Gaia "Earth as organism" hypothesis. *SimCity* was inspired by urban-dynamics models developed by MIT scientist Jay Forrester. The *Sims* games, beneath their animated-dollhouse exteriors, are time-management experiments, based in part on a trove of data gathered by sociologist John Robinson on how Americans spend their hours.

Wright's next game, *Spore,* due out next year, simulates the entire cosmos; he refers to it jokingly as *SimEverything*. The player starts as a microbe in a cell-eat-cell world and gradually advances onto land, evolves sentience, develops culture, forms tribes, cities, and civilizations, and finally acquires the ability to move freely through a breathtakingly vast universe of planets, stars, and galaxies. Everything is malleable: A player can create a creature with, say, 3 legs and 15 eyes and stretch it like clay. The animating software then figures out how best to make it walk, run, and stalk prey. A player can create ringed planets and watch the moons orbit leisurely for hours. Meanwhile, the many worlds in your *Spore* cosmos are pollinated automatically from an online database of plants and animals created by other players.

"As you play, you create the elements of the universe, which are used to populate other players' worlds," Wright says. "In a sense, you're creating the universe for other players. We're making the player the game designer."

Through your games, you come across as a guy who's trying to decipher the natural world bit by bit, through computer simulations.

That's not far off. When I was a kid, I liked taking things apart to see how they worked. Computer simulation is similar, it's reductionist; you've got these parts, you want to see how they interact, so you build a model and compare it to the real world. When you formulate a model, you quickly see your misperceptions. That's the value of simulation in science, to spotlight our ignorance.

Modeling is one of the things that led to an understanding of chaos theory. Back in the 1960s, Dennis and Donella Meadows, a husband and wife team, tried to model the world in terms of things like population, food production, standard of living, and so on to get some sense of where the world was going. When they ran their model, it basically showed the whole world population crashing—quickly, by 1985, according to them. Of course, that didn't come true. Looking back, it became clear that just a couple of variables were off by a few percent and got very amplified. The scientists didn't foresee the green revolution in agriculture—the use of fertilizers and pesticides. So their food production numbers were just a bit low, but it compounded year after year. One little thing off a little bit can have a huge impact on the eventual destination.

What were you doing at age 10 that steered you toward game design?
Building a lot of models—plastic, wood, whatever. That evolved into making things with motors, and that evolved into robots. Robots got me into computers. One of my favorite robots was one called Mr. Rogers. I built it when I was about 20. It had three wheels and an ultrasonic sensor for mapping the room and was attached to an Apple II. I still love robots; it's kind of a background hobby. My daughter, Cassidy—she's 19, she's in art school—was doing *Robot Wars* and *BattleBots* with me for many years.

***Spore* takes its cue from astrobiology, both in its spatial sweep—from microbiology to galaxies—and in the interplanetary spread of life. What turned you on to the subject?**
Well, I've always had an interest in the SETI program, which led me to astrobiology and to Drake's equation. Drake's equation is simple. Basically, you take the average number of stars in the galaxy and you ask what percentage have habitable planets. Then you ask what percentage of those couple of planets does life arise on? - And on what percentage of those is the life intelligent? What's the average life span of that civilization? You crunch all those numbers together and get one that tells you how many intelligent species are out there asking themselves the same question. For some reason, most of these models leave out panspermia [the theory that life may have originated elsewhere in the cosmos]; I love to think panspermia's gotten short shrift. Anyway, all the factors lead back to how unique we are. Stars and galaxies are complex and interesting, but they're still nowhere near as complex as life.

One thing that interests me is that all the factors in Drake's equation map to different size scales. It's almost like an index into science at different scales: chemistry, biology, sociology. As humans we're stuck at the scale of our bodies, but there are all these different levels above and below us; each one has its own dynamics, its own processes, its own timescale. I've always been intrigued by Charles and Ray Eames's *Powers of Ten* book and movie. They really tried to give an overall sense of where we are in the universe, to give some perspective on the history of life. That awareness can make you feel insignificant. But in some sense, it's also the reverse. If we're the only life around, what an incredible responsibility! It's humbling and deeply empowering at the same time.

So *Spore* is an existential game?
One of my original goals was to give players the equivalent of a drug-induced epiphany. I've been surprised, given *Spore*'s epic scale, that it has such broad appeal—that the average person finds some meaning in it. Of course, every player finds a different meaning: how big the universe is, or the existence of different timescales, or how precious life is. The important thing is getting people to step back and enjoy the view.

The *Spore* universe plays like a planetarium show; you've clearly worked hard to model orbital and galactic motions accurately.
You should see all the stuff that's not in the game! We did a huge number of prototypes, modeling almost

anything you can imagine, from autocatalytic chemistry to the dynamics of interstellar gases. For a brief while, we considered making gas giants playable, but not having a solid surface makes game play difficult.

I'm told you collect artifacts from the Russian space program.
I've always had a fascination with it. I'm impressed by their approach and the success they've had compared to NASA. And they've done it at one-fifth the cost. These days you have to hire the Russians to get you into space, not NASA. I like to collect their stuff, take it apart, see how it works. It's incredibly durable, and cheap. I've got control panels from the Mir space station and the complete interior of a *Soyuz* spacecraft. I'm going to Russia next week, actually, to Star City and some other places. A lot of the coolest stuff is down in the basements of these aerospace corporations. I'm going with several friends; it's sort of a space junket.

Would you ever go up in space?
Oh, sure, I'd do it under the right circumstances. But not $20 million to fly in the *Soyuz*.

Do you play computer games besides the ones you design?
Oh, yeah. I spend maybe five hours a week playing games. On the PC, I still play *Battlefield 2* and *Advance War* on my old Game Boy. Lately I've been into *Guitar Hero*. It's a game for PlayStation 2 that comes with a guitar controller, which has buttons on its frets instead of strings. You try to play along to real rock songs, and there's this whole little audience on-screen that'll boo you off the stage if you stink. When you get it right, it's really satisfying.

What makes a game compelling to you?
In the kinds of games I focus on, I'm interested in amplifying the players' natural abilities. I want a player to feel surprised: "Wow, I made this thing!" Then, because you feel ownership over it, you start feeling things like pride—or even guilt if you run the situation badly. People talk about how games don't have the emotional impact of movies. I think they do—they just have a different palette. I never felt pride, or guilt, watching a movie.

A lot of what makes things fun generally is people challenging themselves, learning new patterns. You're building a model in your head that will help you predict what the system's going to do and enable you to perform in that system more accurately. That's why kids play, I think. From a very early age, that's how we relate to the world. We look for patterns, we poke and prod: If I do this, what happens? That's how we learn causality.

So games are fun because they allow us to play with time?
Partly. You can think of games almost as time machines. They allow us to explore the possibility space around a given starting point. You can hit Start Over and do the *Groundhog Day* thing: Relive the same day and try doing this, replay the same day and try doing that. You can control time in a way that you can never do in real life and get some sense of how chaotic a system can be.

Storytelling is the same way. Say I'm a caveman and I almost get killed by a tiger. I can come tell you that I left my cave and a tiger almost got me. I'm sharing an experience and can now influence your behavior. Next time you leave the cave, you'll look out for the tiger. That's a time machine for experience—lessons that we might learn.

You've collected and analyzed thousands of hours of data gathered from people who play *The Sims* online. To what extent is playing *The Sims* a behavioral experiment?
It's an interesting kind of Rorschach test. The way in which people play the game says a lot about their personal interests and creativity. Some focus on giving their Sims skills, climbing the career ladder, building McMansions. Others focus on romance or building a family. Others are into creating a cast of characters and saving it on the Web; for them *The Sims* is more like a set of actors and sets with which to tell stories. It's up to you to decide how you want to make your Sim happy. *SimCity* is like that as well. We don't tell you that you have to build a big city, or a happy city, or a clean city; people come up with their own goal state that has a lot to do with their own value system. The game almost asks them, OK, what do you think a good city is? Or a good life?

You've modeled planetary dynamics, ant colonies, even the way players play your games. What's left?
Do you know about fitness landscapes? It's this idea that you can map evolutionary fitness. If you were *this* genetic combination, you'd be *this* fit. If you were *that* genetic combination, you'd be *that* fit. Any given population is basically climbing a fitness landscape. It's cross-correlated: The shape of the landscape is dependent on what all the organisms are doing, so even as an organism evolves, the landscape is always changing.

I did some modeling of this—fairly long-term models of creatures evolving on different landscapes. Interestingly, the results I got were very similar to punctuated equilibrium [an evolutionary theory championed by Niles Eldridge and Stephen Jay Gould]. You'd see regions of stability for long periods of time, then diversity would go up, then suddenly the whole system would go into chaos, you'd have this mass die-off, and then it would go back up pretty rapidly.

You're doing this for fun? That's what you do on the weekend?
Yeah, pretty much just for fun. I get really into biology. I find it more and more fascinating, especially macroevolutionary stuff. Actually, I think the idea of evolution is one that a lot of people have a hard time wrapping their minds around. They think, oh, you've got this one mutation and then the creature is a little bit better at seeing, therefore it survives. But, in fact, it's much more of a numbers game: You have thousands of creatures that have a slightly better chance of seeing, and statistically they survive 1 percent better. People aren't used to dealing with the numbers and the timescales involved. But once you look at it from that point of view, evolution just seems so much more plausible. It makes perfect sense.

In Wikipedia, *Spore* is described as a "teleological evolution" game. Do you think the game will bring natural selection to the masses?
You can look at it in a number of ways. What's ironic, really, is it's intelligent design. As a player, you go through an arc of being this lowly little cell, being attacked by pond scum, to eventually becoming a god. At the godlike level, you can almost do the whole creationist thing if you want: "I will create a planet; I will create species; I will put them on the planet." But you're a god without a whole lot of foresight. You put all this stuff on a planet,

and it might go kerflooey. You might make a really badly balanced ecosystem. You're not necessarily an omnipotent god. That's even more fun. You have these godlike powers, yet the repercussions of them become totally unpredictable to you.

If you could rebuild Earth in any way—add or subtract any creature or process, for instance—what would you do?
What's my starting point? The Paleolithic?

Now, whenever, any time you want. The world is your oyster.
Hmmm. Well, the development of life was amazing and maybe incredibly improbable, so I wouldn't want to mess that up. The development of intelligence was possibly even more improbable; I wouldn't want to modify anything until that happens either. Even then . . . I wouldn't want to touch it, actually. If I started now, maybe I'd do something to increase the odds of humans surviving on Earth. But maybe not! Can I give you James Lovelock's answer? I'd probably eliminate cattle entirely. They're the Earth's second-largest producers of methane, which is a serious greenhouse gas. The clearing of rain forests is done mainly to accommodate livestock, so getting rid of cattle would help protect biodiversity.

FROM THE SEPTEMBER 2006 ISSUE

The Discover Interview: David Baltimore

The retiring president of Caltech delivers some straight talk on AIDS research, celebrity science, and his role in one of the most talked-about fraud scandals of the past 25 years.

By Susan Kruglinski | Friday, September 01, 2006

RELATED TAGS: HIV & AIDS, STEM CELL RESEARCH

baltimore-225

In molecular biology David Baltimore is a giant. September 1 marks the last day of his presidency at Caltech, and although he will continue to work as a professor, it is the end of an era in a long career that has been as controversial as it has been impressive. For more than a quarter of a century, Baltimore has balanced his long hours as a leading scientific administrator—founder of the seminal Whitehead Institute, president of Rockefeller University and later, for nine years, of Caltech—with groundbreaking work in cancer, immunology, and AIDS research.

Baltimore won the Nobel Prize in 1975 for his surprising discovery that RNA can be transformed into DNA, a process in cells known as reverse transcription. No one then could have predicted the role this discovery would play when a strange new illness began popping up in emergency rooms in 1981. The pathogen responsible, HIV, was found to reproduce using reverse transcriptase (thus it is a retrovirus), and Baltimore has been in the trenches of AIDS research ever since. The oft-quoted biologist has railed against the Bush administration's handling of science and is on the panel that decides how money will be spent on stem cell research in California, via the state's controversial Proposition 71.

But as great as his accomplishments are, Baltimore is perhaps best known for his involvement in one of science's most famous scandals, the so-called Baltimore affair. In 1986 Thereza Imanishi-Kari was accused of fraud when a postdoc questioned the results of published research that Imanishi-Kari had coauthored with Baltimore. The accusations were addressed by Congress, which concluded that data may have been falsified. An appeal to a federally appointed panel led to an exoneration, but Baltimore's vehement insistence that his colleague was innocent in the face of damning evidence led to his resignation as president of Rockefeller University.

Discover caught up with Baltimore on his final presidential vacation at his second home near Missoula, Montana, where his plans to fly-fish were interrupted by our questions about the future of AIDS prevention, the usefulness of stem cell research, and what really happened in the most famous fraud scandal prior to this year's South Korean stem cell debacle.

Why did you decide to step down as president?
I decided that I had done as much as I could and that it was a good time for a new person to take over. I had said it would be about 10 years when I started off. It was 9 years, and that felt just right.

This year marks the 25th anniversary of the first known case of AIDS. Is AIDS research, a quarter century later, where it should be?
AIDS research today suffers a lot from our inability to figure out a route to make a vaccine. The research in the treatment of the disease has gone very well, but what the less-developed world needs, and what we need, too, is

a vaccine. Because of the biology of HIV, it has been extremely difficult to make such a vaccine—and it's not for lack of smart ideas. But the virus always seems to figure out a way around anything that we come up with. We're going to live in a world without an HIV vaccine for at least another decade, at the rate we're going. And we've been saying it's going to be another decade for the last few decades. So it's a very depressing circumstance.

What makes HIV so challenging to a biologist?
The virus has found ways to protect itself—particularly against antibodies—almost completely. It hides in a cloud of sugar—carbohydrates—and it has only a few open spaces on its surface that are not covered in sugar. Those open spaces are so designed that the body finds it difficult to make an antibody that will be able to get in there and block the receptor sites that the virus uses to bind the cell. The end result is that this is one of those very rare diseases—there's hardly another like it—where the virus multiplies continuously at high levels and the immune system is unable to deal with it. What vaccines depend on is the immune system. We know that the standard vaccine simply won't work, and so we have to look for novel ways of making vaccines. But so far no one's come up with an answer.

Is it possible that no one will ever be able to develop a vaccine?
I'm not positive it will be found. This may be a disease that we simply can't vaccinate against. And if you look at the other diseases we can't vaccinate against, they are the major killers in the world—malaria and tuberculosis in particular. We may live in a world where our only protection is educating people to protect themselves.

What kind of AIDS research are you conducting in your lab?
I have a very strange and chancy program in the AIDS area that is funded by the Gates Foundation. We want to use gene therapy methods to protect people against HIV. It is a way to modify cells in the immune system. We use viruses that have been gutted of all their viral genes and use them as vectors. The absent genes are replaced with ones that control the immune system specificity. And then we infect bone marrow cells with the vector—those cells ultimately give rise to the immune system. The vector incorporates itself into the DNA of the cell. Then we put those transformed cells back into an animal or, ultimately, a person. The immune system will be programmed by the genetic changes that we've made. It will now make protective molecules [antibodies and antibody-like proteins] that it otherwise would not make. This would be something that initially would be a therapy after infection, but if it worked, then I'd like to see it developed as a vaccine, if that were at all possible.

Has anybody ever done anything like this—used gene therapy to modify the immune system?
No, only in experimental animals. We've had a lot of success with them. We were working with a cancer model to work out the system. We've also done work in protecting human cells against HIV infection using gene therapy methods. That's in vitro.

Since you are on the panel that oversees the California money for stem cell research, could you compare the controversy over stem cells to past controversies, like IVF? That clearly blew over, and IVF became mainstream. In vitro fertilization was shocking when it first came along, and there was a lot of opposition to it. The United States government has never funded a program for in vitro fertilization. IVF has developed as a totally unregulated industry without a good scientific base because the government was afraid to touch it. So although you are right in saying that everybody's doing it, it's a hospital-based procedure that is unregulated. I don't know what the quality of it is. But a lot of children are being born that way. I think it's absolutely terrific.

But if IVF is unregulated, could there be problems in the long term because nobody is looking at this scientifically?
Absolutely, there could be. Who knows?

So, having seen the IVF controversy, the stem cell controversy was no surprise.
We were sensitized to the fact that stem cells were going to be touchy territory. What was a surprise was that the president of the United States would block the development of a whole field of science as a consequence. If the Democrats get in, or certain Republicans get in, it will change overnight.

And you think at that point the typical American won't even question this science?
That's what I think. Right.

How is the California money being spent?
There is no money being distributed. The whole initiative depends on the issuance of bonds, and the opposition has prevented the bonds from being issued by bringing legal challenges. During a time of uncertainty and with legal challenges ongoing, you can't sell bonds. So the amount of money being given out is quite small. The California initiative was supported by private philanthropists, and so there was some money there. They've given out grants for training purposes to a number of institutions in California. But that's the only money that's been given out. The rest of the time we've spent getting procedures in place and dealing with the bureaucratic issues of setting up this huge funding operation for science, which the state of California never had.

If there had not been a controversy, what do you imagine we'd be able to do right now with stem cells?
I really don't know, because I don't know how hard it's going to be to solve some of the problems. There are fundamental problems. The South Korean debacle [in which scientist Hwang Woo Suk was found to have been conducting fraudulent stem cell research] was revealing because one of the basic technologies that we thought they had developed they were in fact unable to do, and so far nobody in the United States or elsewhere has been able to do it either.

So, like AIDS, is it possible that perhaps 25 years from now we will still be at the beginning, solving the most basic problems?
Yes, but the difference is that there are pretty obviously enormous opportunities for doing good science with stem cells. And whether it becomes therapeutically extremely important or not, I don't know. But I have no doubt that it will be scientifically very important.

What kind of science will we get from them, if not therapeutic?
The major thing we can learn from stem cells is how a program unfolds that leads from an undifferentiated cell to a highly differentiated cell. And we've learned a lot about that in model systems, such as in fruit flies, worms, and mice. But the opportunity to do that with humans is, of course, very limited. To start with human stem cells will be a powerful way to understand what goes on in the development of human physiology. And when development goes wrong, as it does with many diseases, we can study that outside the body.

You are unafraid to say what you feel. What motivates you?
If we scientists want our community to have the respect that it's due, we have to be open and honest. And if we

start playing games and being politicians, then we lose one of the most valuable things that we have, which is our honesty. It doesn't mean we're always right. But it does mean that we're willing to stand by what we believe.

As president of Harvard University, was Larry Summers too outspoken?
Well, if you're talking about what he said about women in science, I think he should have kept that for a purely academic discussion—if he wanted to have an academic discussion about it—and not have done it in circumstances in which it could become public.

Should he have resigned?
I don't think Larry had to resign because of what he said about women. He had lost the confidence of the faculty, and it's very difficult to lead a faculty if they don't have confidence in you.

You had to resign from the presidency of Rockefeller University after only one year because of the fraud scandal. Was that unfair?
It was unfair that it had to happen, but it was not wrong given the circumstances. It had become very difficult for me to function. The chief executive has to have the ability and authority to function.

During your own controversy, you stated that scientists should be trusted and not questioned. Considering all the recent fraud scandals, do you think differently about those statements?
I still feel that the vast majority of scientists are honest about what they do and that fraud is rare. Unfortunately, it has recently happened in very visible circumstances. But science has to be replicated. In the instances in which there is fraud, it will be found out if it is important. If it's not important, then it doesn't matter.

Is there anything you would have done differently in your own case?
There are some things, but I don't particularly want to get into them.

Why did it happen in the first place?
It was the kind of laboratory dispute that occurs, and it just got blown totally out of proportion.

Wasn't there any justification for an accusation of fraud?
I don't even think that it was justified that it got started. I mean, the science was perfectly good. The problem was a personnel problem in a lab, and those kinds of things happen. The problem was that it got out of the lab and into the National Institutes of Health and into Congress.

You're saying that there weren't errors and sloppy work?
There was sloppiness in record keeping. That used to be much more of a problem than it is today, because people are more aware of the need for it today. But in the old days many people took notes on a paper towel, and that's just not acceptable behavior anymore.

Was her work ever replicated?
You know, it's never been exactly replicated to my knowledge. Things very much like it have been done, and there's no reason to doubt that what she saw is correct. As far as I know, the research was completely solid.

In the case of Hwang Woo Suk, being a superstar scientist may have put pressure on him to continually accomplish great things. Are scientists in the United States under pressure to be superstars within their own field?
That's a dangerous pressure in science because it does lead people to cut corners. I don't know that it happens, but it's something to be concerned about. When people become very visible, they may act to try to keep their reputation.

You are a Nobel laureate and something of a science superstar in your field. How do you deal with that?
I try to ignore it as much as possible [laughs]. It's hard with students who see me as somebody who has both been in research for a long time and been quite successful, so I've got to break that down.

Do you think that the popular conception that you are scientifically set for life once you have a Nobel is something of a myth?
Yes, it is absolutely a myth. I know that funding agencies look very carefully at you when you have a Nobel Prize. In fact, they worry that you're over the hill in some way and just trying to coast on a reputation, so they look perhaps even more carefully at proposals from Nobel laureates. There is no open spigot of funds available.

What was the most enjoyable part of your career?
You know, every time I'm involved in an experiment—whether a student of mine is doing it or in the old days when I would do it myself—where there's an unexpected, exciting result, it's just the same thrill all over again. We had some pretty exciting stuff recently, and it's the same thrill. You go home, and you think about it when you go to sleep, and you think about it when you wake up in the morning, and you know there is something new in the world.

Will you ever really retire?
Who knows? Depends what gets me first, right?

FROM THE NOVEMBER 2006 ISSUE

Q&A with Economist Jeffrey Sachs

He's got a plan to save the world. All it needs is a smart dose of science, some enlightened politicians, and about 0.7 percent of your money.

By Corey S. Powell | Monday, November 27, 2006

RELATED TAGS: ENVIRONMENTAL POLICY

Jeffrey Sachs is used to thinking big: His area of expertise is nothing less than our entire planet. As director of the Earth Institute at Columbia University, he worries about climatic changes that could have dire consequences for us all. As director of the United Nations' Millennium Project, he works to save billions of people from disease, hunger, and the other ravages of extreme poverty. And as a leading economist and a special adviser to the Secretary General of the United Nations, he has a unique appreciation of the monetary and political obstacles to tackling these global challenges. In February, at the annual meeting of the American Association for the Advancement of Science in St. Louis, he captivated the crowd with early results from a project in Africa that uses low-cost fertilizers and improved farming techniques to increase crop yields several times over. Sachs travels constantly, not just from country to country but from continent to continent. *Discover* managed to catch him between flights at his home on the Upper West Side of Manhattan.

On the spectrum from microeconomics to macroeconomics, you've gone as macro as possible. What led you in this direction?

I've been interested in one question for—my God!—about 35 years: What makes a society work well? I was lucky to be taken by my parents to the Soviet Union when I was in high school. Communism was a puzzlement. Why would there be a different kind of political system on the same planet? Which one works? Which doesn't? That was a major prod toward looking at what leads to well-being.

After the fall of Communism, you advised governments in Eastern Europe and Russia on their transition to market economies. Did things turn out the way you expected?

I don't think anybody anticipated what the health implications would be. In some parts of central and Eastern Europe, not only did life expectancy rise but heart disease went down a lot: Changes away from high cholesterol and fatty diets helped that. In Russia, on the other hand, life expectancy plummeted, and deaths of middle-aged and older men rose significantly. There is still a big debate about why. Was it alcoholism and stress from the collapse of an empire? Or were more subtle factors involved? Some nutritionists believe that there were small changes in the men's diet that were very adverse, like a low level of some micronutrients, but this is still not proved.

What about the environmental impact?

The whole Soviet system—including Eastern Europe—was incredibly energy intensive, and to a large extent, that meant coal intensive. There was a huge rise in the price of energy after the fall of Communism. So there was a very sharp decrease in fossil-fuel use, and the air improved enormously.

Are the market economies doing much better in terms of environmental sustainability?

The Soviet system was particularly miserable, but it's not as if the market system has really gotten this under control yet. We still have a major conundrum, which is that gross national product, which we take to be an indicator of material well-being in some sense, is highly correlated with energy use. Although energy efficiency is improving, so that the economy can grow maybe 1 to 1.5 percent faster than energy consumption, rising economic output and rising energy use are very powerfully connected. Economic development comes from being able to harness energy sources. Getting by without energy doesn't make sense on a basic physics level because energy is what does our work for us.

So we're not going to conserve our way out of the problem.

That's right. We can and should conserve a lot more, but it won't solve the problem. When you consider that world population will grow by another 50 percent between now and its ostensible peak around midcentury and that you have massive economic growth in today's poor countries, energy use is going to rise significantly.

Won't increasing energy use make global warming worse?

The challenge is to deploy energy sources that are safe, reliable, plentiful, and environmentally sound. Anthropogenic climate change is an extraordinarily important issue, which we have done a remarkable job of neglecting up to this point. But climate change is not caused by energy use. Climate change is caused by greenhouse gases. The question is: Are there ways to deploy energy resources without creating greenhouse gases, particularly carbon dioxide?

You recently coauthored a paper on some possible answers. What do you see as our most promising options?

Renewable or noncarbon forms of energy generation—solar power, wind, hydroelectric, nuclear—have to play a role. In addition, there is what we call carbon management, which is the big hope we have at the Earth Institute. It's proved at a very small scale and plausible, although unproved, at a much larger scale. Basically, you use fossil fuels in an environmentally sound way by making sure that carbon dioxide is not emitted into the atmosphere but instead collected and put safely underground. What's unknown is whether that can be done on a global basis. Roughly 25 billion tons of carbon dioxide are produced each year, and that's a lot of storage.

How can we find out if carbon management will scale up?

We should sit down with our counterparts in India, China, Brazil, Russia, and the European Union and build a number of thermal power plants with carbon management, so we learn how this technology works. What are the costs? What are the risks? What are the regulatory problems? What is the geologic storage capacity? Where should power plants be located if we're going to go this way?

Why aren't we doing that already?

Although the Bush administration says that technology offers the biggest promise of a way out of our environmental problems, the lassitude of the administration is shocking and shameful, because there is a complete disconnect between the importance of the issue and the casualness with which it's treated—not to mention deliberate obfuscation as well. The president is deliberately running from this issue, so there's no leadership whatsoever.

It's not just the president, of course. Much of the American public is still skeptical about climate change too.

The public needs to understand that we are contributing to grave danger worldwide. Climate change is not just an issue for the future. We're in the middle of it right now. That signal is translating into all sorts of events—droughts, intense rainfall, more intense tropical cyclone activity, crop stress, heat waves, and so on.

But it's not easy to demonstrate cause and effect—for instance, that a particular storm is the result of global warming.

It is absolutely true that climate scientists are extremely cautious about attributing any event to anthropogenic climate change, but an increasing number of such attributions are being made with high confidence in the scientific literature now. One breakthrough paper was about the European heat wave of 2003, where modeling showed that under the hypothesis of unchanged climate, the frequency of such a heat wave occurring was something like once in 5,000 years. The conclusion of the authors was: If this would normally happen only once in every 5,000 years, yet this event is consistent with the model of anthropogenic climate change, then there's really a good, logical reason to attribute this heat wave to man-made change.

At the same time, many people both here and abroad worry that addressing global warming will kill the economy.

We have a lot of screaming that, in my best guess, is really powered by vested interests. There is a lot of fear. But what Klaus Lackner and I showed in the paper we published last year is that the cost of deflecting our trajectory away from a doubling of carbon emissions, using optimistic but plausible technological projections, looks to be significantly below 1 percent of gross world product. If carbon emissions doubled, the risks to millions of species, to ecosystems, to farming, to sea levels, and to all the rest would be huge. Now, if the world were told this clearly and asked, "Should we head this off at a cost of between 0.1 percent and 0.3 percent of gross world product?" the answer would, in my opinion, be overwhelmingly yes.

In your role as director of the U.N.'s Millennium Project, a lot of your work concerns Africa. Why have so many countries in Asia been able to develop while Africa has not?

Poorer countries have benefited from the diffusion of technologies developed elsewhere. Certain kinds of technology, like cell phones or the Internet, can work essentially anywhere. But when you think about health, agriculture, or construction, there is an ecologically specific challenge. In the case of Africa, conditions are tougher, and diffusion has been weaker. Take malaria. Malaria is an absolutely devastating disease for Africa. Africa's ecology is uniquely suited to malaria transmission. But it's a disease that Americans hardly care about. Our biggest research on malaria has come when American soldiers have been fighting in tropical countries, like the Pacific Islands in World War II or in Vietnam. When we're not in the middle of a tropical war, malaria concerns in this country disappear. So there's Africa, which has holoendemic malaria—it's everywhere—and it's an incredible burden on the society and on the economy, but almost no work gets done on it. This has been recognized for years but not particularly acted upon until the Gates Foundation came along and restarted or energized a lot of research for diseases of the poor. Agriculture is another area where Africa has it tougher.

You've noted that the green revolution passed Africa by. Why?

The green revolution in the 1960s was a package of technologies that included high-yield variety seeds combined with fertilizer and small-scale water management. That package was the critical step out of extreme poverty for Asia. But it did not apply in Africa. The first high-yield seed varieties were wheat, which is a temperate-zone crop, and paddy rice, which is an irrigation-based technology. Wheat and rice being improved was good for India and China, but it was largely irrelevant for the staple cassava or maize crops in Africa. Now, by the 1980s African high-yield seed varieties were becoming available. But at that point you had a technology that was too expensive for impoverished farmers to use, and the philosophy of the United States and the World Bank was, "If they can't buy it, it must not be useful to them." The vast majority of African farmers are still planting low-yield seeds without even the benefit of fertilizer, and the harvests that they're getting are a third or a fourth or a fifth of what they ought to be getting, and the result is mass hunger.

How are the Millennium Project and the U.N. helping?

We are operating a partnership with villages across Africa called Millennium Villages. We're testing easily deployed technologies: bed nets to combat malaria, high-yield seeds, fertilizer. We hypothesize that at a low cost one can have an enormous effect on the quality of life. We're in the second year of a five-year project, and the results are astounding. Each harvest that we've had, first in Kenya, then in Ethiopia, and recently in Malawi and in Rwanda, has tripled or quadrupled the amount of food produced. We believe the villages will earn enough income so that after five years they'll be able to take on the expense of these technologies. The idea is not only to show that you can grow more food but that you can make an economic transformation that's self-sustaining. We see increased food production as the entry point into the breakout from extreme poverty. This is, in essence, how India's escape from extreme poverty got started.

What else is the Millennium Project doing?

World leaders have agreed on goals for the project: to fight poverty, hunger, disease, and the deprivation of basic needs like safe drinking water and sanitation. Such goals are often adopted with the tacit understanding that they are good for a speech or a headline, but the view is, "Oh, don't take them seriously, they're just words." My assignment is to take them seriously and remind the world not only that we've agreed to do these things but that they are achievable and vitally important. I am trying to mobilize scientists, technologists, the corporate sector, and civil society all to say that practical things can be done that will make a difference in the fight against suffering and instability. Last year, all the European donor countries committed to spend 0.7 percent of their GNP in foreign aid. If they actually honor those commitments, that's a phenomenal breakthrough.

The United States didn't join that commitment, even though Americans are, in my experience, very generous people. Why?

One reason is that we're diverted constantly by war. Yet there is overwhelming evidence to show that the probability of a country falling into conflict, either civil war or cross border, is higher the poorer the country is. The CIA, which established something called the Political Instability Task Force years ago, has found this repeatedly. It's actually part of our national security doctrine—the economic development of poor regions is part of U.S. national security. President Bush has made statements not different from mine. He just doesn't advocate the funding that could make this work. From my own experience—I've worked with well over 100 governments around the world—positive inducements are extremely powerful. Negative inducements, like military force, generate resistance, nationalism, and fear, which easily spiral out of control. Whenever we've invested in development, whether it was European reconstruction, Korea and Taiwan in the 1950s, or the green revolution, the long-term benefits have been huge. Whenever we have let places collapse under the weight of extreme poverty, whether Afghanistan or the West Bank, we've ended up paying horrendous consequences.

It sounds as if you're trying to establish a new kind of international ethics, rooted in science and economics.

When I discuss morality, it's not about natural law. I view morality in a very instrumental way: Can we live together without killing each other? We need principles that address the difficulty of surviving and prospering on a crowded planet. We are not tribal bands off on our own in our own part of the forest. We're absolutely on top of each other, and that requires a kind of practical ethics we don't have yet.

What do you think the world will be like 50 years from now?

I believe there is a clear path to shared prosperity through knowledge and science. I also believe there is a very real possibility of an environmental, health, or military catastrophe. Fundamentally, this is about choice. The future is not a roulette wheel that we sit back and watch as worried spectators. It's a matter of work. We should see the risks, see the positive possibilities, and do what we can to make sure that future outcomes are the ones that we desire.

FROM THE JANUARY 2007 ISSUE

Discover Interview: Marvin Minsky

The legendary pioneer of artificial intelligence ponders the brain, bashes neuroscience, and lays out a plan for superhuman robot servants.

By Susan Kruglinski | Saturday, January 13, 2007

RELATED TAGS: ROBOTS, NEUROSCIENCE


Image courtesy of Donna Coveney/MIT

Marvin Minsky straddles the worlds of science and sci-fi. The MIT professor and artificial intelligence guru has influenced everyone from Isaac Asimov to the digital chess champ Deep Blue to computer movie star HAL of *2001: A Space Odyssey*. He may be known around campus as "Old Man Minsky," but the scientist is just as active in AI research today as he was when he helped pioneer the field as a young man in the 1950s.

Although educated in mathematics, Minsky has always thought in terms of mind and machine. For his dissertation at Princeton University in the 1950s, he analyzed a "learning machine," meant to simulate the brain's neural networks, that he had constructed as an undergrad. In his early career he was also an influential inventor, creating the first confocal scanning microscope, a version of which is now standard in labs worldwide. In 1959 Minsky cofounded the Artificial Intelligence Laboratory at MIT, where he designed and built robotic hands that could "feel" and "see" and manipulate objects, a watershed in the field.

Throughout, Minsky has written philosophically on the subject of AI, culminating in the 1985 book *Society of Mind*, which summarizes his theory of how the mind works. He postulates that the complex phenomenon of thinking can be broken down into simple, specialized processes that work together like individuals in a society. His latest book, *The Emotion Machine*, continues ideas begun in *Society of Mind,* reflecting twenty-some additional years of thought. It is a blueprint for a thinking machine that Minsky would like to build—an artificial intelligence that can reflect on itself—taking us a step forward into a future that may seem as if out of an Asimov story.

What are your latest ideas about the mind, as set out in *The Emotion Machine?*

The theme of the book is that humans are uniquely resourceful because they have several ways to do everything. If you think about something, you might think about it in terms of language, or in logical terms, or in terms of diagrams, pictures, or structures. If one method doesn't work, you can quickly switch to another. That's why we're so good at dealing with so many situations. Animals can't imagine what the room would look like if you change that couch from black to red. But a person has ways of constructing mental images or sentences or bits of logic.

Neuroscientists' quest to understand consciousness is a hot topic right now, yet you often pose things via psychology, which seems to be taken less seriously. Are you behind the curve?

I don't see neuroscience as serious. What they have are nutty little theories, and they do elaborate experiments to confirm them and don't know what to do if they don't work. This book presents a very elaborate theory of consciousness. *Consciousness* is a word that confuses possibly 16 different processes. Most neurologists think everything is either conscious or not. But even Freud had several grades of consciousness. When you talk to neuroscientists, they seem so unsophisticated; they major in biology and know about potassium and calcium channels, but they don't have sophisticated psychological ideas. Neuroscientists should be asking: What phenomenon should I try to explain? Can I make a theory of it? Then, can I design an experiment to see if one of those theories is better than the others? If you don't have two theories, then you can't do an experiment. And they usually don't even have one.

So as you see it, artificial intelligence is the lens through which to look at the mind and unlock the secrets of how it works?

Yes, through the lens of building a simulation. If a theory is very simple, you can use mathematics to predict what it'll do. If it's very complicated, you have to do a simulation. It seems to me that for anything as complicated as the mind or brain, the only way to test a theory is to simulate it and see what it does. One problem is that often researchers won't tell us what a simulation didn't do. Right now the most popular approach in artificial intelligence is making probabilistic models. The researchers say, "Oh, we got our machine to recognize handwritten characters with a reliability of 79 percent." They don't tell us what didn't work.

Neuroscientists like Oliver Sacks and V. S. Ramachandran study people who have brain injuries; to them, what is not happening in the brain is more informative than what is happening. Is that similar to what you're saying?

Yes. In fact, those are just about the two best thinkers in that field. Antonio Damasio is pretty good, but Ramachandran and Sacks are more sophisticated than most. They consider alternative theories instead of trying to prove one particular theory.

Is there other work in neuroscience or AI that interests you?

Very little. There are 20,000 or 30,000 people working on neuronetworks, and there are 40,000 or 50,000 people working on statistical predictors. There are several thousand people trying to get logical systems to do commonsense thinking, but as far as I know, almost none of them can do much reasoning by analogy. This is important because the way people solve problems is first by having an enormous amount of commonsense knowledge, like maybe 50 million little anecdotes or entries, and then having some unknown system for finding among those 50 million old stories the 5 or 10 that seem most relevant to the situation. This is reasoning by analogy. I know of only three or four people looking at this, but they're not well-known because they don't make grandiose claims of looking for a theory of everything.

Can artificial intelligence have human-style common sense?

There are several large-scale projects exploring that issue. There's the one that Douglas Lenat in Texas has been pursuing since 1984. He has a couple of million items of commonsense knowledge, such as "People live in houses" or "When it rains, you get wet," which are very carefully classified. But what we don't have are the right kind of answers to questions that a 3-year-old child would be filled with. So we're trying to collect those now. If you ask a childlike question like, "Why, when it rains, would somebody want to stay dry?" it's confusing to a computer, because people don't want to get wet when it rains but they do when they take a shower.

What is the value in creating an artificial intelligence that thinks like a 3-year-old?

The history of AI is sort of funny because the first real accomplishments were beautiful things, like a machine that could do proofs in logic or do well in a calculus course. But then we started to try to make machines that could answer questions about the simple kinds of stories that are in a first-grade reader book. There's no machine today that can do that. So AI researchers looked primarily at problems that people called hard, like playing chess, but they didn't get very far on problems people found easy. It's a sort of backwards evolution. I expect with our commonsense reasoning systems we'll start to make progress pretty soon if we can get funding for it. One problem is people are very skeptical about this kind of work.

Usually AI refers to an exploration of the utilitarian uses of the brain, like understanding speech or solving problems. Yet so much of what humans do isn't clearly utilitarian, like watching TV, fantasizing, or joking. Why is all that behavior necessary?

Watching sports is my favorite. Pleasure, like pain, is thought of as being a sort of simple, absolute, innate, basic thing, but as far as I can see, pleasure is a piece of machinery for turning off various parts of the brain. It's like sleep. I suspect that pleasure is mainly used to turn off parts of the brain so you can keep fresh the memories of things you're trying to learn. It protects the short-term memory buffers. That's one theory of pleasure. However, it has a bug, which is, if you gain control of it, you'll keep doing it: If you can control your pleasure center, then you can turn off your brain. That's a very serious bug, and it causes addiction. That's what I think the football fans are doing—and the pop music fans and the television watchers, and so forth. They're suppressing their regular goals and doing something else. It can be a very serious bug, as we're starting to see in the young people who play computer games until they get fat.

Many people feel that the field of AI went bust in the 1980s after failing to deliver on its early promise. Do you agree?

Well, no. What happened is that it ran out of high-level thinkers. Nowadays everyone in this field is pushing some kind of logical deduction system, genetic algorithm system, statistical inference system, or a neural network—none of which are making much progress because they're fairly simple. When you build one, it'll do some things and not others. We need to recognize that a neural network can't do logical reasoning because, for example, if it calculates probabilities, it can't understand what those numbers really mean. And we haven't been able to get research support to build something entirely different, because government agencies want you to say exactly what you'll do each month of your contract. It's not like the old days when the National Science Foundation could fund people rather than proposals.

Why has the landscape changed for funding scientific research?

Funders want practical applications. There is no respect for basic science. In the 1960s General Electric had a great research laboratory; Bell Telephone's lab was legendary. I worked there one summer, and they said they wouldn't work on anything that would take less than 40 years to execute. CBS Laboratories, Stanford Research Lab—there were many great laboratories in the country, and there are none now.

***The Emotion Machine* reads like a book about understanding the human mind, but isn't your real intent to fabricate it?**

The book is actually a plan for how to build a machine. I'd like to be able to hire a team of programmers to create the Emotion Machine architecture that's described in the book—a machine that can switch between all the different kinds of thinking I discuss. Nobody's ever built a system that either has or acquires knowledge about thinking itself, so that it can get better at problem solving over time. If I could get five good programmers, I think I could build it in three to five years.

It sounds like you could make a very smart computer, but is your ultimate goal to actually reproduce a human being?

Or better. We humans are not the end of evolution, so if we can make a machine that's as smart as a person, we can probably also make one that's much smarter. There's no point in making just another person. You want to make one that can do things we can't.

To what purpose?

Well, the birthrate is going down, but the population is still going up. Then we're going to have old people, and we'll need smart people to do their housework, and take care of things and grow the vegetables. So we need smart robots. There are also problems we can't solve. What if the sun dies out or we destroy the planet? Why not make better physicists, engineers, or mathematicians? We may need to be the architects of our own future. If we don't, our culture could disappear.

Has science fiction influenced your work?

It's about the only thing I read. General fiction is pretty much about ways that people get into problems and screw their lives up. Science fiction is about everything else.

What did you do as consultant on *2001: A Space Odyssey*?

I didn't consult about the plot but about what the [HAL 9000] computer would look like. They had a very fancy computer with all sorts of colored labels and so forth. Stanley Kubrick said, "What do you think of that?" I said, "It's very beautiful." And he said, "What do you *really* think?" I said, "Oh, I think this computer would actually just be lots of little black boxes, because the computer would know what's in them by sending signals through its pins." So he scrapped the whole set and made the simpler one, which is more beautiful. He wanted everything technological to be plausible. But he wouldn't tell me what HAL would do.

If we developed the perfect artificial brain, what would be the difference between that and the real thing?

Well, it wouldn't die. Some people believe that you should die, and some people think dying is a nuisance. I'm one of the latter. So I think we should get rid of death.

FROM THE MARCH 2007 ISSUE

The Discover Interview: Jane Goodall

For 47 years, Goodall has studied, communicated with, and lived with chimps.

By Virginia Morell | Wednesday, March 28, 2007

RELATED TAGS: PRIMATES, ENVIRONMENTAL POLICY


All images Courtesy of the Jane Goodall Institute.

Four decades ago, a leading zoologist dismissed Jane Goodall as an amateur. She agreed. “My future is so ridiculous,” she wrote. “I just squat here, chimp-like, on my rocks, pulling out prickles and thorns, and laugh to think of this unknown ‘Miss Goodall’ who is said to be doing scientific research somewhere.”

But within a few months of beginning her study of chimpanzees in 1960, insinuating herself into their lives in the forests of Africa,she made a shocking discovery: Chimpanzees construct tools. Legendary anthropologist Louis Leakey announced that because of Goodall’s observations, “we must redefine tool, redefine man, or accept chimpanzees as human.” She soon gained entrance to a doctoral program at Cambridge University, even though her highest previous degree was from a secretarial school, and was well on her way to becoming a scientific icon.

To this slim, ponytailed young woman, chimps looked more clever, more scary, and often more human than anyone had ever suspected. They hunt, sometimes engage in cannibalism, make war on each other, adopt orphans, and drum on tree roots and wave branches in ritual-like displays. Some chimps are cunning politicians; others seem devoted to their families.

Fame and age have broadened Goodall’s focus. These days she spends most of her time on the road, lecturing and raising funds for the Jane Goodall Institute (check their blog) and its efforts to assist wild and rescued chimpanzees. But she still keeps close tabs on her adopted family, the African primates who took her in.

When you arrived in Africa, did you imagine you’d be spending 47 years involved with chimpanzees?
No [laughs]. How could I have back then? One year there seemed enormous at the time. I was only 23. I was invited to Africa by a school friend whose parents had moved to Kenya. One of their friends said, “If you’re interested in animals, you should meet Dr. Louis Leakey.” So I went to see him at the Coryndon Museum [where Leakey was director], and he ended up offering me a job as his secretary. During the time I worked for him, I had the opportunity to go out on the Serengeti with him. He knew I didn’t care about clothes and hair,dresses and parties, and that I really, really, really wanted to live with animals in the bush. And that I didn’t care about a degree—I just wanted to learn.

What is your fondest memory of observing the chimps in Tanzania?
When I would sit quietly with a family and watch the interactions between mother and child, brothers and sisters. Yes, it was amazing to see tool use for the first time, but it didn’t really surprise me that they could do

that. I hadn't been to college and didn't realize how exciting this observation was. Ironically, about three weeks after[field biologist] George Schaller visited me for the first time, I saw[chimpanzee] David Greybeard using a tool. George had said during his visit to my camp, "If you see tool using and hunting, it will have made the whole study worthwhile." Within a month, I'd seen both.

Watching the chimpanzees, did you ever long to be one?
Sometimes I did, especially in the early days when it was just me and the chimps and the forest. I just wanted to know what they were thinking and feeling, and what it felt like in the evening to be making a nest, and what it felt like to be a female when a big male comes thundering in. Are you afraid or excited? It was impossible to tell.

Did you immediately recognize distinctive personalities among the chimpanzees?
It took a long time before they lost their fear of me. But as I got to know them and watched them interact, their personalities became very obvious. There were mean ones and generous ones, aggressive ones and gentle ones.

To many people, you are the scientist who made chimps seem almost human. Is that how they appear to you?
They kiss, embrace, hold hands, pat one another on the back, swagger, shake their fists, and throw rocks in the same context that we do these things. There are strong bonds of affection and support between family members. They help each other. And they have violent and brutal aggression, even a kind of primitive war. In all these ways, they're very like us.

Was the violence frightening? You were attacked once by a chimp named Frodo when you tried to help him.
Well, he was only being a young male. When they bash you, they aren't trying to hurt or kill you. If they were, I wouldn't be here, because they are eight times stronger than me. So it's just showing off, just bravado. If he's scaring off other chimps, then why not me?

If chimps are so much like us, why are they endangered while humans dominate the globe?
Well, in some ways we're not successful at all. We're destroying our home. That's not a bit successful. Chimpanzees, gorillas, orangutan shave been living for hundreds of thousands of years in their forest,living fantastic lives, never overpopulating, never destroying the forest. I would say that they have been in a way more successful than us as far as being in harmony with the environment.

Yet they never evolved to our intellectual level. Why?
What makes us human, I think, is an ability to ask questions, a consequence of our sophisticated spoken language. Chimps have something like the beginning of morality, but once you have language—once you can discuss something and talk about it in the abstract and take lessons from the past and plan for the future—that is what makes the difference.

FROM THE APRIL 2007 ISSUE

Raw Data: Beacon Bird of Climate Change

Penguin poop reveals secrets of the Antarctic climate.

By Josie Glausiusz | Wednesday, April 04, 2007

RELATED TAGS: UNUSUAL ORGANISMS, GLOBAL WARMING

THE STUDY "A 45,000-Year-Record of Adélie Penguins and Climate Change in the Ross Sea, Antarctica" by Steven Emslie, Larry Coats, and Kathy Licht in the January 2007 issue of *Geology*.


Adélie penguins leave debris that contains clues to shifting ice sheets.

(Courtesy of Steven Emslie)

THE MOTIVE For millions of years, Antarctica's ice sheet has - advanced and retreated as Earth has cooled and warmed. Covering nearly 5.5 million square miles, the frozen mass exerts an enormous influence on the global climate, reflecting sunlight back into space and cooling Earth's atmosphere and oceans. If the ice sheet were to melt, global temperatures would rise 8 to 10 degrees Celsius. Yet dating past expansions and contractions of the Antarctic ice shelf has proved difficult. Geologists can infer its changing size by dating marine sediments, but this method is not always accurate. Now Steve Emslie, a marine ornithologist at the University of North Carolina Wilmington, has developed an ingenious method of tracking climate change in the Antarctic: He has excavated and carbon-dated 45,000 years' worth of Adélie penguin poop, skin, bones, feathers, and eggshells from colonies preserved in Antarctica's frigid climate. Because these birds nest only on ice-free terrain, the presence of their ancient nesting sites indicates when the glacial ice sheet had retreated; their absence indicates the ice had returned.

THE METHODS Beginning in 2001, Emslie began burrowing into the remains of 28 abandoned and 8 active Adélie penguin colonies on islands and coastline abutting the Ross Sea, which fills the cleft in the continent where it meets the South Atlantic Ocean. Adélies are two-foot-tall birds that feed on krill, fish, and squid and build their nests from small beach pebbles in colonies that may occupy the same site for thousands of years.

Because Antarctica's dry, cold conditions preserve penguin detritus, each colony accumulates piles of guano, as well as old feathers, eggshells, and bones, especially those of chicks. "If you dig into an active penguin colony, the sediments will be jet black and tarry and gooey—that's just degrading guano and pebbles," says Emslie. Once the colony is abandoned, it dries out, and the sediments acquire a reddish tint derived from the pigment in krill. These deposits often contain more than mere fragments. "In some sites I find whole penguin mummies—I've got one that's a thousand years old," says Emslie. "It's like a squashed chick without most of the feathers but with skin and bones still dried together."

To date the deposits, Emslie and his coworkers measured out three pits of one square meter (about 10 square feet) at each site, then excavated samples at two-inch intervals, going down one to two feet until they reached the bottom layer of bird detritus, deposited when the site was first occupied. The researchers washed each sample by hosing it down in a sieve and then radiocarbon-dated the remains they extracted from each level. (All organisms take in carbon-14, a rare radioactive isotope, while they are living; when they die, the carbon decays at a steady rate. By placing samples in a mass spectrometer and counting the concentration of carbon-14 atoms remaining, researchers can estimate the age of the samples.)

Antarctica's oldest penguin-breeding colony, Emslie discovered, was at Cape Hickey in the south of the Ross Sea, containing eggshells from 43,000 to 27,000 years ago, while a nearby island molting site had two feathers older than 44,000 years. That indicates that the sea was then open water. Over the next 14,000 years, the ice shelf advanced and did not begin retreating again until about 13,000 years before the present, when the last ice age ended. About 8,000 years ago, Adélie penguins returned to the Ross Sea coastline, building new colonies until two cool periods—between 5,000 to 4,000 years ago and 2,000 to 1,100 years ago—forced them to abandon most nesting sites. Only one colony, at Inexpressible Island, appears to have been occupied continuously for the past 7,000 years. Another, at Cape Adare in the north, is the largest active Adélie penguin colony in Antarctica; it is home to more than 150,000 nests and is 2,000 years old.

THE MEANING "Penguin colonies have been blinking in and out of the Ross Sea over time with climate change," says Emslie, and this research puts "a better absolute date on when there was open water, which is the first time we've been able to do that." Prior to this work, geologists did not know exactly when the Ross ice shelf began to advance. Thanks to Emslie's penguin findings, "we now know that it had to have been after 27,000 years ago." The results also have profound implications for present-day climate change, says Ólafur Ingólfsson, a glacial geologist at the University of Iceland in Reykjavik. "We know very little about how rapid environmental changes are in Antarctica," he says, and yet "what happens in Antarctica will spread like ripples throughout the global system." Emslie's data will now allow geologists to calibrate models of past climate change and so make better climate predictions. "What Steve is doing is absolutely brilliant," Ingólfsson says.

FROM THE APRIL 2007 ISSUE

Paul Allen Discusses Dreams of Space

Microsoft's co-founder throws his fortune at the frontiers of science.

By Evan Ratliff | Monday, April 23, 2007


(Courtesy of Brian Smale)

Make a list of common boyhood dreams and Paul Allen will very likely have lived most of them. Start your own company and make a gazillion dollars? Check. Own two professional sports teams? Check. Play lead guitar in rock band? Check. Build a rocket to fly people into space? Check. Make giant telescope to search for aliens? Check. Crack the mystery of the human brain? Well, he's working on it.

The seminal moment in the life of one of the world's wealthiest men is often pegged as the time, in 1975, when he persuaded his high schoolfriend Bill Gates to drop out of Harvard University and co-found a company called Microsoft. But since leaving the software giant in 1983after being diagnosed with Hodgkin's lymphoma—and then facing down the disease—Allen has lived a dizzying array of second lives. Drawing on his Microsoft-stock fortune, today estimated at $22 billion, he has funded dozens of companies in the software, cable, and Web industries,bought the Portland Trail Blazers and Seattle Seahawks, and built Seattle's Experience Music Project, the rock-and-roll history museum.Along the way, Allen has also become a leading patron of the sciences,whose influence can rival that of huge government agencies.

Back when he was a high school guitar player obsessed with software,Allen was mesmerized by movies like *2001: A Space Odyssey* and Jacques Cousteau's *The Silent World*. Thirty years later, he started steering his fortune toward projects that could easily belong in those movies. In 2001 his $11.5 million investment helped jump-start the SETI program, a methodical search for radio signals from intelligent life.(The new Allen Telescope Array will start sweeping the sky for aliens this year.) His love of rockets spurred a $30 million gamble on *SpaceShipOne*, which won the X Prize as the first manned craft in suborbital space. In 2003 Allen doled out $100 million to found the Allen Institute for Brain Science, with the ambitious goal of mapping all gene expression in the mammalian brain. Last September the institute released a complete genomic map of the mouse brain—a free,searchable, three-dimensional analysis of 21,000 genes (including 85million images) that will help neuroscientists understand how different regions of the brain operate and interact. Now Allen plans to move onto the big prize: mapping the human neocortex.

In his Seattle office—with a glass-encased replica of his 416-footyacht, the *Octopus*, in front of him and the Seahawks' stadium visible from the window—Allen spoke with DISCOVER about funding priorities, Microsoft memories, and which childhood dream he plans to check off next.

Do you ever wonder what the world would be like today if Microsoft had never existed?
Whoa. If Microsoft had never existed. . . . The industry would probably be very fragmented. But there are so many new models that have sprung up—things like the iPod, Google, YouTube, eBay, and Amazon. Soit's like asking, "What if there wasn't an Amazon?" Well, there would probably be other people online selling books, but would it have the impact of an Amazon? Probably not. Or what if there were five companies doing online auctions and not just eBay? For users, there may be a bigger variety of things to choose from, but whenever you have scale, obviously you have more of a chance to make it a better product. The bigger you get, the more inertia you have, which is good. On the other hand, you don't want to get so big that you struggle to get releases out. So there is always that tension.

Has your experience with Microsoft shaped the kinds of scientific projects you are supporting today?
In a way. In the computer industry, you've got an interdisciplinary team of people who can come together, attack the problem, and work in a collaborative style. You knock down one problem after another, cobble things together, and then hopefully turn the crank at some point. This is what we did with the mouse brain project.

Your interest in the workings of the brain seems like a logical step for someone who started out writing software.
Yeah, if you are involved in computers, at some point you end up being fascinated by the idea of the human brain. The human brain works in a completely different fashion from a computer and does some things so much better than a computer, and this may remain true for the next 100, 200 years. How can that be? So I brought a bunch of neuroscientists together and asked, "What can I do that would be interesting and different that would potentially help the field of neuroscience move forward?" The answer was a genetic database of the mouse brain.

"The human brain works in a completely different fashion from a computer and does some things so much better. . . . How can that be?"

The Allen Brain Atlas is, at heart, a massive data-archiving project. Is this type of research a trend in science?
It's kind of industrial-scale science, where the output, the product, is a database. I think we are already seeing some efforts to do genetic databases of cancer; I believe there is a Harvard effort under way. Craig Venter has his project where he collects seawater [in an effort to catalog ocean life]. But we are probably only talking about dozens of these kinds of databases at this point. That may end up being naive a few decades from now.

What's next at the Allen Institute for Brain Science?
There are still parts of the mouse brain that we need to explore: the developmental mouse brain, the female brain differences. Then we are starting to scale up to the human brain. It's so much bigger than the mouse brain, which is kind of an almond-size thing. You need bigger slides, more digital capacity. And of course there is no uniform strain—thank goodness—of human beings, like there is of mice. But I think trying to parse out the detailed genetics and structure of the brain will go a long way to understanding how it works.

What do you think are the chances of SETI's succeeding—in other words, of finding intelligent life beyond our world?
The scientists are optimistic because they think that if they have better instruments that look deeper or on more

frequencies, there should be civilizations out there broadcasting. I think everybody would admit it's a long shot, but if that long shot comes in... wow.

If they do get the signal, will you be the first person they call?
Actually, first they call the White House. At one point they told me I was third or fourth on the list. So I guess that's one of the benefits of funding the project. But the phone hasn't rung yet.

What would that kind of discovery mean to you?
That would be such a life-changing thing, for us all to know that there are other beings out there who we could potentially communicate with, or maybe we are listening to a signal that they transmitted hundreds of millennia ago. And then we'd say, "Well, what was in the message? Can we decode the message, and can we communicate back? What are they really like? Are they oxygen-breathing bipeds, or are they a gas cloud on some gas-giant planet?"

You've also supported the more practical aspects of space exploration, funding SpaceShipOne. What was it like to watch SpaceShipOne take off?

I just remember being so nervous when that thing flew, hoping everything was going to be OK. I had never done anything to put anyone's life at risk. When you are debugging a program, if it blows up, OK, you get an error message on the screen. If something goes wrong with a rocket, it's usually... bad. Very bad.

What do you think of Richard Branson and Burt Rutan's effort to turn *SpaceShipOne* into a commercial venture?
Burt Rutan is a genius of aeronautic design; I remember him scribbling some designs for the first version of *SpaceShipOne* that weren't that far from how it ended up. If you are going to do something like that, he's one of the few people in the world who could pull it off. Branson's proposed *SpaceShipTwo* is still using the fundamental technology from the *SpaceShipOne* project, just of much bigger breadth.I think it's going to be great if people can buy a ticket to fly up and see black sky and the stars. I'd like to do it myself—but probably after it has flown a serious number of times first!

Do you support NASA's plans to send humans back to the moon and on to Mars?
You have to make an argument—which I think people do make with some persuasiveness—that this is about having an aspirational vision. Don't we get the same data back if we have a little track vehicle running around Mars with a TV camera? I think there is actually a difference,having a human being out there. But I'm always fascinated by technical challenges. Human beings are fragile things, and for the period of time it takes to get them to Mars and back you have dangerous radiation from the sun and the galaxy. We have to think about issues like that. As a species, we've always been discoverers and adventurers, and space and the deep ocean are some of the last frontiers. I'm less certain that someone is going to be selling beachfront property on the Martian sea.

The projects you have funded so far cover a wide range of fields. What are the criteria you look for?
I ask myself: What are the great questions in science, the knowledge that we are just

"The chance that we aregoing to pick up the phone and an alien is going to be on the other endis small, but it is certainly worth it."

scratching the surface of? The chance that we are going to pick up the phone and an alien is going to be on the other end is small, but it is certainly worth—on a modest scale, for me—seeing if we can enable some of that research. There are these greenfield areas like the human brain, systems biology, understanding how cells work internally, and how the proteins interact inside the cell. That's an area I'm thinking about. Then there are the global issues we have today: global warming, the environment, and disease. I don't know that I could make a difference in theoretical physics; that's basically a bunch of mathematical and theoretical geniuses at different places. I'm not sure how anyone could make them work any faster than they are.

When you fund the Brain Atlas or *SpaceShipOne*, do you think of them as investments or philanthropy?
I think of them as philanthropy, but then the next thought is, Is there a way to make this thing self-funding? In the case of biological research, it means that you are either going to have to carve out some patents or try to create funding from other foundations or the government. I think we are going to have success with the Brain Atlas because the capabilities that we have demonstrated are pretty unique.But with that project we haven't taken the route of getting proprietary intellectual property—not that I'm excluding it. Most of the things I've ever done, I try to capture some value and keep it going. And my gosh, look at Microsoft. In 1975 it was three guys, and now it's 70,000.

When you and Gates started out, how ambitious were you?
We knew that microcomputers with software on them could have some impact, and certainly they were cheap. A big part of the success of Microsoft was that every year, the chips our software ran on got faster and cheaper. They doubled in capability every 18 months under Moore's law. Even to this day, every year they get better and the price doesn't change. It's amazing, and that was a huge driver of our success. When we were starting Microsoft, we were thinking if we were really successful we would have something like 35 employees. On the other hand, in the back of our minds we were thinking, "Wow, if a lot of people bought a cheap computer . . . " We had glimmerings of it.

How did the collaboration between the two of you work in those early days?
We split the programming tasks. I was familiar with the software that ran on mainframes and minicomputers that will let you emulate chips. And Bill bit off some of the really complicated stuff and did agreat job architecting the overall design of the Basic program. Bill was always very focused on the external relationships and the business management part of it, whereas I was more attracted toward seeing where the leading edge of the technology was going. So we were a good complement to each other.

Do you guys reminisce about the old times?
Yes, we always have a laugh because it's hard to explain the incredible level of fun we had. We talk about how Bill would sleep on the carpet at the office. The secretary would come in and see Bill's feet sticking out of the door. We were very hard-core. Our only recreational activity was going to the movies. And then we would program until two, three, four in the morning and then get up fairly late, go back, and do it again. We just loved it. We had a great time.

In a weird way you and Gates still seem to follow parallel paths. Do you ever talk about entering a philanthropic collaboration?
We are always looking to find some areas of overlap in our philanthropic stuff. We've had so much success

doing things before; it feels good. Recently we've been talking about doing something together on the frontiers of energy.

What are the biggest questions on your mind right now?
The health of the planet, whether it's ocean health or energy.Should nuclear energy make a comeback? We have an investment in a fusion energy company that is quite interesting.

What kind of fusion research are you investing in?
The company is called Tri Alpha Energy [which finances aneutronicfusion, a process that emits protons rather than neutrons, potentially making it much more efficient than current concepts]. Fusion has been predicted to be just over the horizon for decades now, so whenever you see an interesting alternative approach, you think about it. There has been a lot of discussion recently on fission reactors, and I have been involved in doing some survey meetings recently. I think Bill is intrigued by that too. But it's really speculative.

So you've got computers, sports, boats, space, science, rock and roll. Is there any childhood love you have left to get into?
When I was 7 or 8 I became fascinated with hot rods. I don't own one. But I'm not as fascinated by them as I am by many other things. So no Model T with the super V-8 and the flames painted on the side. In life, you need to pick your spots.

FROM THE MAY 2007 ISSUE

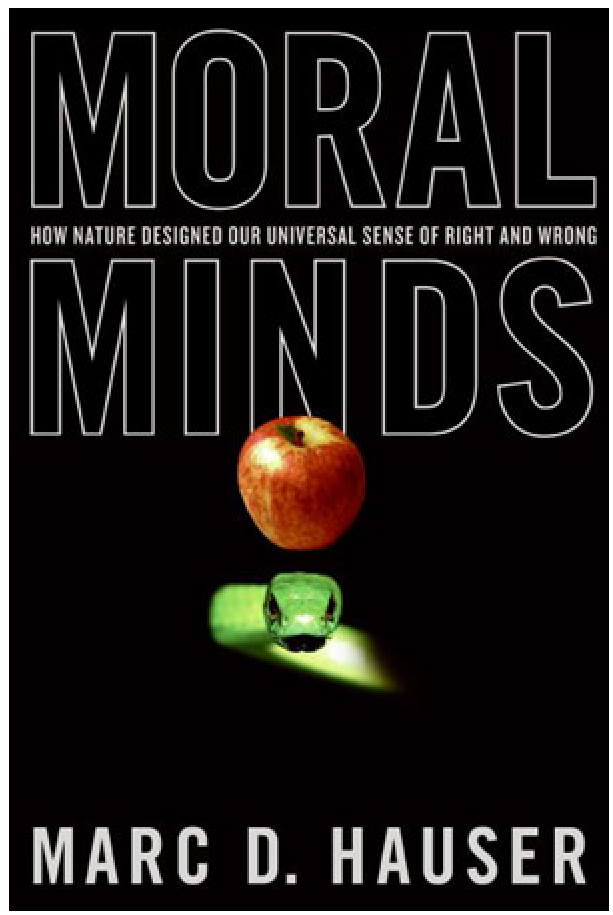
Is Morality Innate and Universal?

A hardwired moral code leaves a lot of room for interpretation.

By Josie Glausiusz, Doron Gild | Thursday, May 10, 2007

RELATED TAGS: MEMORY, EMOTIONS, & DECISIONS

A healthy man walks into a hospital where five patients are awaiting organ transplants. Is it morally acceptable to kill the man in order to harvest his organs to save the lives of five others? If you instantly answered no, you share a near-universal response to the dilemma, one offered by peoples and cultures all over the globe. (Test your moral instincts here.) But how did you reach this conclusion? Was it a rational decision learned in childhood, or was it—as Harvard evolutionary biologist and cognitive neuroscientist Marc Hauser claims—based on instincts encoded in our brains by evolution? In his recent book *Moral Minds: How Nature Designed Our Universal Sense of Right and Wrong* (HarperCollins), Hauser argues that millions of years of natural selection have molded a universal moral grammar within our brains that enables us to make rapid decisions about ethical dilemmas. (Read a review here.)



To arrive at this radical notion, Hauser draws on his own research in social cooperation, neuroscience, and primate behavior, as well as on the musings of philosophers, cognitive psychologists, and most important, the theories of MIT linguist Noam Chomsky, who in the 1950s proposed that all humans are equipped with a universal linguistic grammar, a set of instinctive rules that underlie all languages. Hauser himself, a professor of psychology, human evolutionary biology, and organismic and evolutionary biology at Harvard and codirector of the school's Mind/Brain/Behavior Initiative, has analyzed the antics of tamarins, vervet monkeys, macaques, and starlings in captivity, as well as rhesus monkeys and chimpanzees in the wild. This research led to his earlier book *Wild Minds: What Animals Really Think* (Owl Books, 2001).

You argue that humans have an innate moral faculty. Can you describe what you mean by this?
The basic idea is to ask about the sources of our moral judgments. What are the psychological processes involved when we deliver a moral judgment of right or wrong? The crucial issue to keep in mind here is a distinction between how we judge and what we do. In some cases, our judgments may align very closely with what we would actually do, but on occasions they may be very, very different.

The second point is to draw on an analogy with language and ask whether there might be something like a universal moral grammar, a set of principles that every human is born with. It's a tool kit in some sense for building possible moral systems. In linguistics, there is a lot of variation that we see in the expressed languages throughout the world. The real deep insight of Chomskian linguistics was to ask the question, "Might this variation at some level be explained by certain common principles of universal grammar?" That allows, of course, for every language to have its own lexicon. The analogy with morality would simply be: There is going to be a suite of universal principles that dictate how we think about the nature of harming and helping others, but each culture has some freedom—not unlimited—to dictate who is harmed and who is helped.

What is the evidence that we draw upon unconscious principles when making moral decisions?
Let's take two examples. A trolley is coming down a track, and it's going to run over and kill five people if it continues. A person standing next to the track can flip a switch and turn the trolley onto a side track where it will kill one but save the five. Most people think that's morally permissible—to harm one person when five are saved. Another case is when a nurse comes up to a doctor and says, "Doctor, we've got five patients in critical care; each one needs an organ to survive. We do not have time to send out for organs, but a healthy person just walked into the hospital—we can take his organs and save the five. Is that OK?" No one says yes to that one. Now, in both cases your action can save five while harming one, so they're identical in that sense. So why the flip-flop? People of different ages, people of different religious backgrounds, people even with different educations typically cannot explain why they think those cases differ. There appears to be some kind of unconscious process driving moral judgments without its being accessible to conscious reflection.

FROM THE JUNE 2007 ISSUE

David Brin Predicts the Future

Sci-fi author knew all about the Web, global warming, and more.

By David Kushner, Brigitte Sire | Thursday, June 07, 2007

RELATED TAGS: COMPUTERS

David Brin works out of his home office in San Diego County, but he spends much of his day in invisible worlds—ones hidden from us because we can't perceive them or because they don't even exist yet. For the past three decades, the Hugo Award–winning author has been mapping out his vision of the future in dozens of works, both nonfiction and sci-fi. His 1998 book, *The Transparent Society*, explores how technological innovations force us to choose between privacy and security, foreshadowing the era of YouTube and ubiquitous surveillance cameras. His 1990 novel, *Earth*, anticipates so many of today's trends—from the World Wide Web to global warming—that there is a Web site devoted entirely to its prognostications.

How did this 56-year-old father of three, who lives mostly outside of academia, get so adept at parsing the future? By keeping his journeys of imagination grounded in the real world. After getting a master's in electrical engineering at the University of California at San Diego, Brin completed a Ph.D. in space physics and worked as a postdoc at the Jet Propulsion Laboratory. Today, in addition to churning out novels that chart his fictional Uplift universe, he continues to work closely with the people developing technologies that will transform our lives.

Why do you have such a good track record as a prognosticator?

When prediction serves as polemic, it nearly always fails. Our prefrontal lobes can probe the future only when they aren't leashed by dogma. The worst enemy of agile anticipation is our human propensity for comfy self-delusion.

Peering ahead is mostly art. We all have tricks. One of mine is to look for "honey-pot ideas" drawing lots of fad attention. Whatever's fashionable, try to poke at it. Maybe 1 percent of the time you'll find a trend or possibility that's been missed. Another method is even simpler: Respect the masses. Nearly all futuristic movies and novels—even sober business forecasts—seem to wallow in the same smug assumption that most people are fools. This stereotype led content owners to envision the Internet as a delivery conduit to sell movies to passive couch potatoes. Even today, many of the social-net and virtual-world companies treat their users like giggling 13-year-olds incapable of expressing more than a sentence at a time of actual discourse.

A contrarian trick that has served me well is to ponder a coming technology and then imagine, What if everybody gets to use it? In really smart ways? Most of those imaginings have come true.

What's the biggest trend you've failed to spot or the biggest prediction you think you got wrong?

Back in 1999, I forecast that people would shrug off future shock when the big millennium rolled around. At first it seemed that way, as people blithely went about their routines. Now I suspect there really was a 21st-century trauma. Romantic nostalgia is rampant. You find very little interest in the modernist agenda of confident problem solving. Robert Heinlein predicted this, but I didn't. I also expected a few technologies that never came. For example, lie detection based on involuntary eye movements, a method that ought to work even during a televised interview or press conference. A potential nightmare for deceitful politicians! But I was misled by hope. Other disappointed forecasts include rapid understanding of the immune system and big advances in computerized teaching.

At the other end, some trends exceeded anticipation. I did not expect the "age of amateurs" to progress so far, so fast. Fifty million hobbyists are demanding that professionals, from doctors to scientists to movie directors, accept a new world where expertise is not limited to the licensed.

You have said that science's ability to look beyond the familiar is subject to our psychological, as well as physical, ability to perceive. What do you mean?

There is a famous, but much-debated, anthropological myth that the Carib Indians were unable to perceive the first European ships offshore until one of their shamans sat and contemplated for a while and then explained it to them. I think the people are smarter than that, but as an oversimplifying metaphor, it does point out that what we are able to see depends upon a variety of things. Let me give you a real way to put it into perspective. In the 15th century, we got the printing press. Printing is a way of augmenting human memory. Printing not only vastly expanded the ability to convey human knowledge and memory to other people but also made it more robust.

People tend to assume that when things like this happen, it automatically results in an improved humanity. This is what you're hearing from the techno-transcendentalists on the Internet. It is a religious statement that what we're seeing on the Internet today is improving discourse and improving democracy and improving markets. I'm very skeptical of that because at the beginning of any of these revolutions, always what is empowered is demagoguery. The immediate outcome of the printing press was the Thirty Years' War. The immediate outcome of radio was the empowerment of demagogues like Huey Long and especially Adolf Hitler. It always takes a while for the people to learn how to use the new media critically, to be able to perceive the good from the bad.

Now we have computing and databases, expanded memory, television and mass media. We're headed toward the day that databases become a knowledge mesh; we're going to have super memory and super vision. But what is going to enable us to perceive *better*?

Are there some examples of how science is helping us perceive better right now?

There is the basic, ever-increasing power of instrumentation. You have electron microprobes, which are involved in the cutting edge of nanotechnology, for instance. You're able to measure the field of individual atoms. You are able to come up with wonderful crackpot notions like Wil McCarthy's concept of Programmable Matter—that if you were to adjust the electrons on the surface of a sheet of silicon and control them through simple voltages, you could effectively make that surface of silicon behave like iron. We wouldn't have been able to imagine this concept without the ability to operate on an atom-by-atom level.

But the rate at which we are seeing better with telescopes and probing better with microscopes is not where the real action is. Sure, every year we can see smaller; sure, every year we can see farther, but the real breakthroughs are coming in our ability to make more of these observations and do it faster. For instance, lo at the recent use of the Cosmic Evolution Survey, using the Hubble Space Telescope to study gravitational lensings [in which the gravitational pull of galaxies and dark matter bends the light from more distant objects] in an area of the sky nine times the apparent surface area of the full moon. To be able to take a patch of sky and unleash computers to find so many gravitational lensings you could then make a three-dimensional depth map billions of light-years deep so you can find the patchiness of dark matter—that is very impressive. That's the difference between seeing a pixel and deriving information about things that are far away from that pixel. That's a matter of perception.

What is the biggest change you see coming?

I believe that the real breakthrough is connected to something I referred to in *The Transparent Society*, and that's the distribution of power. For example, low-cost screening methods will lead to personalized diagnostic therapy. People are talking about inexpensive methods to screen for millions of biomolecules. Try to imagine what it will be like when cyberneticists do to their room-size laboratories what others did to the room-size computers of the past. And of course, it's going to pose a great many problems to us. Because when pimple-faced teenage hackers can't mess up just your Web site but they can also synthesize any known or unknown organic compound and then go to work at a fast food joint, are you gonna eat fast food under those circumstances? The fundamental thing that's always made a difference in every revolution is the distribution of power. That's my main theme—it's not about fast-paced changes in how small or big or penetrating we can see individually. What's very fast-paced is the spreading of seeing in parallel. It's happening in biochemistry. It's happening in astronomy. It's happening in almost every source of perception.

How will the distribution of power help expand our understanding of the world?

Consider that NASA can't continue to find killer asteroids as they were commanded to do because they don't have the budget. Within five years, amateurs will take over this task. You are going to have asteroid surveys in 10,000 backyards with incredibly sophisticated CCD cameras that feed into loyal robots that are searching the sky in order to make their owner famous. It is the distribution of instrumental power that is driving our new ability to see.

"For privacy and freedom to survive, we'll need a civilization that is mostly open and transparent"

Take a petaflop [1 quadrillion calculations per second] computer. Some years ago I was at the first petaflops conference where they were discussing what uses people might have for such powerful devices when we finally get them. Now we've got them. One way to visualize what a petaflop computer can do is to put a ball on a narrow pedestal in the middle of the desert and take all the light coming in at that ball from every angle. It takes a petaflop to perceive light coming in simultaneously from all those angles. It is one of those things that computers can do that we can't. The fovea of our eye sees only a tiny bit, and then the brain stitches together a mosaic—a marvelous, illusory mosaic—that we are actually looking out at, maybe, a hundred degrees. But a petaflop computer can take in and process photons from every direction at once. We are going to reach the point where no part of the sky is not being looked at at any given time. This will be the age of amateurs.

How does it feel to see your earlier ideas vindicated? These days, with ubiquitous cell phone cameras and YouTube, almost everyone has the power to document and distribute. You were

thinking about that 10 years ago in *The Transparent Society*. Why do you think it's one of the five major public policy books that's still in print? Back in 2001, when the Patriot Act was proposed, I kept getting e-mails that said, "P206!" and at first I didn't get it. Then I turned to page 206 of *The Transparent Society*, and it says roughly, "Suppose at some point we take a major hit and, for example, terrorists ever brought down both World Trade Center Towers. What would the Attorney General ask for?" Then I went through what basically was a mild and more reasonable version of the Patriot Act, because I never pictured John Ashcroft. I suppose I could say, "I told you so." But by now I would have expected some of the other aspects I predicted to be a little stronger, like vigorous activity by whistle-blowers.

Do you worry about the loss of privacy as both the government and amateurs have more and more access to surveillance?

I got some of my nicest letters based on Chapter 9 of *The Transparent Society*, because I really disassemble my own theory, and I talk about all sorts of ways a transparent society could go wrong. You could have a really nasty version of majority rules. I believe that Ray Bradbury shows that in *Fahrenheit 451*. The thing I use to counterbalance that is this: If you look at the last 50 years, whenever the public learns more about some eccentric group, it judges that group on one criterion, and this is always the one it uses: Is this group mean? Are they harmful and oppressive to others? When the answer is yes, the more you learn about the group, the less they're tolerated. If the answer is no, the more you learn about the group, the more they're tolerated.

If that's true and if it holds in the future—if people continue to defend other people's eccentricities because a) they think it's cool to live in a world of harmless eccentrics and b) for the sake of their own protection—then you would likely see a 51 percent or 60 percent or 70 percent dictatorship by a majority that insists on crushing intolerance. Now, that is a group-think majority-imposed will, but it's probably the least harmful one you can imagine. As far as privacy itself is concerned, I have a simple answer to that. Human beings want it. We naturally are built to want some privacy. If we remain a free and knowing people, then sovereign citizens will demand a little privacy, though we'll redefine the term for changing times.

The question really boils down to: Will tomorrow's citizens be free and knowing? Will new technologies empower us to exert reciprocal accountability, even upon the mighty? It may seem ironic, but for privacy and freedom to survive, we'll need a civilization that is mostly open and transparent, so that each of us may catch the would-be voyeurs and Big Brothers.

What does the enormous expansion of human perception imply about our future?

The theological implications are profound. As Einstein said, "There is no reason to believe that the laws of nature had to be so beautiful or so easily comprehended." He thought we were intended to engage in conversation with the Creator, if there is one, and become apprentices. The notion of a humanity of apprentice Creators is implicit in everything that's going on right now. That's why you see scientists assiduously avoiding any discussion of what we're doing as being an apprentice Creation, even though it's blatantly obvious. It's right there in front of us, but we cannot see it—just like the Carib could not see the ships.

Would you rather be living 100 years from now, when we'll presumably have access to so many more answers?

Is it better to sow than to reap? Jonas Salk said our top job is to be “good ancestors.” If we in this era meet the challenges of our time, then our heirs may have powers that would seem godlike to us—the way we take for granted miracles like flying through the sky or witnessing events far across the globe. If those descendants do turn out to be better, wiser people than us, will they marvel that primitive beings managed so well, the same way we’re awed by the best of our ancestors? I hope so. It’s poignant consolation for not getting to be a demigod.

FROM THE JULY 2007 ISSUE

Sun's Shifts May Cause Global Warming

Physicist says carbon dioxide's no big deal.

By Marion Long | Monday, June 25, 2007

RELATED TAGS: GLOBAL WARMING, SOLAR SYSTEM, STARS

Most leading climate experts don't agree with Henrik Svensmark, the 49-year-old director of the Center for Sun-Climate Research at the Danish National Space Center in Copenhagen. In fact, he has taken a lot of blows for proposing that solar activity and cosmic rays are instrumental in determining the warming (and cooling) of Earth. His studies show that cosmic rays trigger cloud formation, suggesting that a high level of solar activity—which suppresses the flow of cosmic rays striking the atmosphere—could result in fewer clouds and a warmer planet. This, Svensmark contends, could account for most of the warming during the last century. Does this mean that carbon dioxide is less important than we've been led to believe? Yes, he says, but how much less is impossible to know because climate models are so limited.

There is probably no greater scientific heresy today than questioning the warming role of CO2, especially in the wake of the report issued by the United Nations Intergovernmental Panel on Climate Change (IPCC). That report warned that nations must cut back on greenhouse gas emissions, and insisted that "unless drastic action is taken . . . millions of poor people will suffer from hunger, thirst, floods, and disease." As astrophysicist ? Eugene Parker, the discoverer of solar wind, writes in the foreword to Svensmark's new book, The Chilling Stars: A New Theory of Climate Change, "Global warming has become a political issue both in government and in the scientific community. The scientific lines have been drawn by 'eminent' scientists, and an important new idea is an unwelcome intruder. It upsets the established orthodoxy."

We talked with the unexpectedly modest and soft-spoken Henrik Svensmark about his work, the criticism it has received, and truth versus hype in climate science.

Was there something in the Danish weather when you were growing up that inspired you to study clouds and climate?

I remember being fascinated by clouds when I was young, but I never suspected that I would one day be working on these problems, trying to solve the puzzle of how clouds are actually formed. My background is in physics, not in atmospheric science. At the time when I left school and began working, it was almost impossible to get any permanent work whatsoever in science. That was why, after doing a lot of physics on short-term things at various places, I took a job at the Meteorological Society. And once I was there I thought, "Well, I had better start doing something." So I started thinking about problems that were relevant in that field, and that was how I started thinking about the sun and how it might affect Earth.

It was a purely scientific impulse. With my background in theoretical physics, I had no—well, certainly not very much—knowledge about global warming. I simply thought that if there is a connection to the sun, that would be very interesting, and I certainly had no idea it would be viewed as so controversial.

In 1996, when you reported that changes in the sun's activity could explain most or all of the recent rise in Earth's temperature, the chairman of the United Nations Intergovernmental Panel called your announcement "extremely naive and irresponsible." How did you react?

I was just stunned. I remember being shocked by how many thought what I was doing was terrible. I couldn't understand it because when you are a physicist, you are trained that when you find something that cannot be explained, something that doesn't fit, that is what you are excited about. If there is a possibility that you might have an explanation, that is something that everybody thinks is what you should pursue. Here was exactly the opposite reaction. It was as though people were saying to me, "This is something that you should not have done." That was very strange for me, and it has been more or less like that ever since.

So it's difficult to do climate research without being suspected of having a hidden agenda?

Yes, it is frustrating. People can use this however they want, and I can't stop them. Some are accusing me of doing it for political reasons; some are saying I'm doing it for the oil companies. This is just ridiculous. I think there's a huge interest in discrediting what I'm doing, but I've sort of gotten used to this. I've convinced myself the only thing I can do is just to continue doing good science. And I think time will show that we are on the right track.

Do you ever worry that people will take your findings and use them to support unwarranted or even harmful conclusions?

I would be happy to kill the project if I could find out that there was something that didn't fit or that I no longer believed in it. When we started, it was just a simple hypothesis based on a correlation, and correlations are, of course, something that could be quite dubious, and they could go away if you get better data. But this work has only strengthened itself over the years.

What first made you suspect that changes in the sun are having a significant impact on global warming?

I began my investigations by studying work done in 1991 by Eigil Fiin-Christensen and Knud Lassen Fiin-Christensen. They had looked at solar activity over the last 100 years and found a remarkable correlation to temperatures. I knew that many people dismissed that result, but I thought the correlation was so good that I could not help but start speculating—what could be the relation? Then I heard a suggestion that it might be cosmic rays, changing the chemistry high up in the atmosphere. I immediately thought, "Well, if that is going to work, it has to be through the clouds."

That was the initial idea. Then I remembered seeing a science experiment at my high school in Elsinore, in which our teacher showed us what is called a cloud chamber, and seeing tracks of radioactive particles, which look like small droplets. So I thought to myself, "That would be the way to do it." I started to obtain data from satellites, which actually was quite a detective work at that time, but I did start to find data, and to my surprise there seems to be a correlation between changes in cosmic rays and changes in clouds. And I think in early January 1996, I finally got a curve, which was very impressive with respect to the correlation. It was only over a short period of time, because the data were covering just seven years or something like that. So it was almost nothing, but it was a nice correlation.

How exactly does the mechanism work, linking changes in the sun with climate change on Earth?

The basic idea is that solar activity can turn the cloudiness up and down, which has an effect on the warming or cooling of Earth's surface temperature. The key agents in this are cosmic rays, which are energetic particles coming from the interstellar media—they come from remnants of supernova explosions mainly. These energetic particles have to enter into what we call the heliosphere, which is the large volume of space that is dominated by our sun, through the solar wind, which is a plasma of electrons, atomic nuclei, and associated magnetic fields that are streaming nonstop from the sun. Cosmic-ray particles have to penetrate the sun's magnetic field. And if the sun and the solar wind are very active—as they are right now—they will not allow so many cosmic rays to reach Earth. Fewer cosmic rays mean fewer clouds will be formed, and so there will be a warmer Earth. If the sun and the solar wind are not so active, then more cosmic rays can come in. That means more clouds [reflecting away more sunlight] and a cooler Earth.

Now it's well known that solar activity can turn up and down the amount of cosmic rays that come to Earth. But the next question was a complete unknown: Why should cosmic rays affect clouds? Because at that time, when we began this work, there was no mechanism that could explain this. Meteorologists denied that cosmic rays could be involved in cloud formation.

You and a half-dozen colleagues carried out a landmark study of cosmic rays and clouds while working in the basement of the Danish National Space Center. How did you do it?

We spent five or six years building an experiment here in Copenhagen, to see if we could find a connection. We named the experiment SKY, which means "cloud" in Danish. Natural cosmic rays came through the ceiling, and ultraviolet lamps played the part of the sun. We had a huge chamber, with about eight cubic meters of air, and the whole idea was to have air that is as clean as you have over the Pacific, and then of course, to be able to control what's in the chamber. So we had minute trace gases as you have in the real atmosphere, of sulfur dioxide and ozone and water vapor, and then by keeping these things constant and just changing the ionization [the abundance of electrically charged atoms] in the chamber a little bit, we could see that we could produce these small aerosols, which are the basic building blocks for cloud condensation nuclei.

So the idea is that in the atmosphere, the ionization is helping produce cloud condensation nuclei, and that changes the amount and type of clouds. If you change the clouds, of course, you change the amount of energy that reaches Earth's surface. So it's a very effective way, with almost no energy input, to change the energy balance of Earth and therefore the temperature.

There were so many strange surprises, and many times we were busy just trying to understand what was going on. The mechanism we seemed to be finding was very different from any theoretical ideas about how it should work. It seemed to be much more effective than we had ever imagined. It seems as if an electron is able to help form a small particle—a molecular cluster, as we call it—and then the electron can jump off and help another one. So it's like a catalytic process. It was a big surprise that it is so effective.

These types of experiments had not really been done before, and we had to find new techniques in order to do them. Once we had the results, it was necessary to understand completely what was going on. So it was a very intense period of work, almost hypnotic.

Now there are other experiments, like the CLOUD project, also designed to investigate the effects of cosmic rays. How will this build on your work?

CLOUD is an international collaboration [sponsored by the European Organization for Nuclear Research, or CERN] that is taking place in Geneva, but it's going to take a while before any results come out of that. It was approved last year, and building the machine will take at least three years. That's a problem with science: You have to have a lot of patience because results are very slow to come.

If the scientists at CLOUD are able to prove that cosmic rays can change Earth's cloud cover, would that force climate scientists to reevaluate their ideas about global warming?

Definitely, because in the standard view of climate change, you think of clouds as a result of the climate that you have. Our idea reverses that, turns things completely upside down, saying that the climate is a result of how the clouds are.

How do you see your work fitting into the grand debates about the causes of global warming and the considerations of what ought to be done about it?

I think—no, I believe—that the sun has had an influence in the past and is changing climate at the present, and it most certainly will do so in the future. We live in a unique time in history, because this period has the highest solar activity we have had in 1,000 years, and maybe even in 8,000 years. And we know that changes in solar activity have made significant changes in climate. For instance, we had the little ice age about 300 years ago. You had very few sunspots [markings on the face of the sun that indicate heightened solar activity] between 1650 and 1715, and for example, in Sweden in 1696, it caused the harvest to go wrong. People were starving—100,000 people died—and it was very desperate times, all coinciding with this very low solar activity. The last time we had high solar activity was during the medieval warming, which was when all of the cathedrals were built in Europe. And if you go 1,000 years back, you also had high solar activity, and that was when Rome was at its height. So I think there's good evidence that these are significant changes that are happening naturally. If we are talking about the next century, there might be a human effect on climate change on top of that, but the natural effect from solar effect will be important. This should be recognized in the models and calculations that are being used to make predictions.

Why is there such resistance to doing that? Is the science that conflicted or confusing? Or is politics intervening?

I think it's the latter, and I think it's both. And I think there's a fear that it will turn out, or that it would be suggested, that the man-made contribution is smaller than what you would expect if you look at CO_2 alone.

Have you had a hard time getting funding?

For an eternity, I would say. But there are no oil companies funding my work, not at all. It sounds funny, but the Danish Carlsberg Foundation—you know, the one who makes beer—they have been of real support to me. They have a big foundation; in Denmark it's one of the biggest resources for science. It's because the founder of

Carlsberg wanted to use scientific methods to make the best beer. It's probably the best beer in the world, because of science.

If cosmic radiation is in fact the principal cause of global warming, is that good or bad news for human beings?

That's a good question because you would have to say that we cannot predict the sun. And, of course, that would mean that we couldn't do anything about it.

But if humans, through carbon dioxide emissions, are affecting climate less than we think, would that mean we may have more time to reduce the harmful effects?

Yes, that could of course be a consequence. But I don't know how to get to such a conclusion because right now everything is set up that CO_2 is a major disaster in society.

Do you agree that carbon dioxide is having at least some impact on Earth's current warming?

Yes, but you have to give the sun a role. If you include the sun in the right way, the effect of CO_2 must be smaller. The question is, how much smaller? All we know about the effect of CO_2 is really based on climate models that predict how climate should be in 50 to 100 years, and these climate models cannot actually model clouds at all, so they are really poor. When you look at them, the models are off by many hundreds percent. It's a well-known fact that clouds are the major uncertainty in any climate model. So the tools that we are using to make these predictions are not actually very good.

What do you hope to do next in pursuit of your theory?

I'm extremely excited about our next experiment, which will happen in the next couple months. We are planning to go one kilometer below Earth's surface because when we do an experiment in the basement we cannot get rid of the radiation. Cosmic rays are so penetrating that there's always ionization in our chamber and we cannot get to zero ionization. I think it will be the first time that people are attempting an experiment where there is no ionization present. I think it will be quite fascinating because it will tell us something about the details in the mechanism.

Do you think then that individuals and societies as a whole need to try to conserve energy? Do you use compact fluorescent lightbulbs, for instance?

Yes, yes, we use those. And I ride a bicycle. There are good reasons to conserve our resources and find a more economical way of using energy, but the argumentation is not linked necessarily to climate.

At this stage in your work, how confident are you that your basic theories are correct?

I think it is almost certain that cosmic rays are responsible for changes in climate. I think now I have very good evidence, and I think I've come up with some very good evidence that it is clouds. Of course, we cannot discuss the exact mechanism, but I think we have some very important fragments of these ideas. One extrapolation w could make, for instance: Would this mechanism work in an ancient atmosphere? Would these processes still happen? That is something I don't know.

You discuss your work as part of an emerging field that you call "cosmoclimatology." What is that?

It is the idea that processes in space and what is happening here on Earth are connected. It is this idea that when Earth is in a certain spiral arm of the Milky Way, you can associate that with a certain geological period. Previously, the idea was of Earth as a sort of isolated system on which processes evolved. Now all of a sudden it seems as if our position in the galaxy is important for what has happened and is happening here on Earth. It is this connection between Earth and space that's exciting and why I have given it this name. Most of this research has taken place just within the last 10 years, and it is truly multidisciplinary, ranging from solar physics and atmospheric chemistry to geology and meteorology—even high-particle physicists are involved. The people who are doing space-related observations are very happy that there could be a connection from space to Earth because it makes a good argumentation for understanding processes out there.

These connections, which combine such a variety of disciplines and create opportunities for many lines of work, are surprising and wonderful. It has been a real challenge for me, though, because I have to look at so many different fields in order to work.

You've faced more than a few hard knocks in pursuing your scientific career. What keeps you going?

From the beginning, I have found this to be a really interesting problem, and now, I think, it is the potential of it that draws me on. It is something which started as a simple idea and seems to be continually extending, or expanding. That has really been the most important thing. I mean, for instance, I would never have thought that we would find these correlations between the cosmic rays and the evolution of the Milky Way and life on Earth. I never expected that all of these things are connected in a beautiful way.

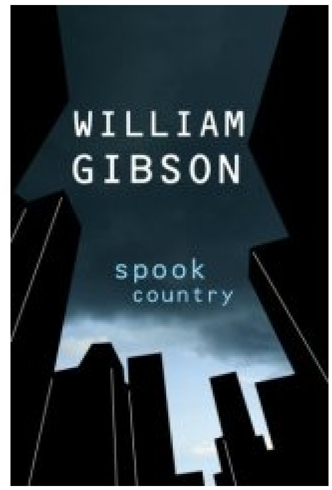
FROM THE AUGUST 2007 ISSUE

William Gibson on the Past and Future

Somehow, cyberspace and the real world switched places.

By Marion Long | Monday, July 30, 2007

RELATED TAGS: COMPUTERS



In 1984, *Neuromancer* by William Gibson became the first novel to win the three top prizes for science fiction (the Hugo, the Nebula, and the Philip K. Dick awards). It established a new literary subgenre —"cyberpunk," or digital, fiction—and helped inspire the Matrix film trilogy. In his debut novel, Gibson coined the term "cyberspace" and described the Internet and virtual reality long before they were part of the cultural landscape. In subsequent works, such as *Count Zero*, *Mona Lisa Overdrive*, *Johnny Mnemonic*, *Virtual Light*, and *Pattern Recognition*, he continued his habit of prescience, forecasting developments in such complex and diverse fields as nanotechnology, identity theft, virtual art, computer viruses, and information control.

Oddly, Gibson, a former English major, knows little about computers or technology of any kind. And he has always insisted that his fiction was a way to comment on the present day and not to suggest the future. Indeed, his latest work, *Spook Country* —a high-style political techno-thriller out this month—actually takes place in the (very recent) past, February 2006. The affable and thought-provoking writer talked with DISCOVER from his home in Vancouver, British Columbia.

The publicity materials call *Spook Country* "a contemporary novel of political paranoia." Do you agree?

To the extent that it's an American novel of its time, I think it's necessarily a novel of political paranoia. Cyberpunk's got it right. In *Neuromancer*—although it's never dated in the book, I always assumed it was happening around 2035—you glimpse the United States, and it's not that great a place. There doesn't seem to be any middle class. There's nothing between these post-human superrich people and the Street, with a capital S. Nobody's ever more than one door away from the Street. It's quite grim and maybe it's become a kind of cliché, but on the other hand, it's exactly like Mexico City. It's really similar to a lot of the Third World. And so I think that the cyberpunk future, if you want to generalize it, is a future in which globalization really does work both ways, and everybody—unless they're very, very, very rich—winds up getting to be part of the Third World.

How do you account for your ability to identify and write about things before other people perceive them?

It sometimes must have involved leaps of induction that I wasn't conscious of. And the way I experience it myself, it's like pattern recognition. Something fits in a certain way. For instance, I remember the first time I saw a picture of a personal computer of any kind: It was sort of portable-looking, and it had a little handle. I knew that everybody would have one of those, and from that, knowing nothing about the technology and all the things they would have to overcome to get there, I just took it for granted that everybody's machine would be connected with everybody else's and that they'd be typing to one another, or whatever it was they did. In that regard, I guess I got it right, but I think I got it right because of the profundity of my ignorance. Because when I was doing that, there were guys who already had their own kind of Radio Shack computers that they'd built, and I knew some of those guys, and I would talk to them and say, "Yeah, they're going to hook them all up, and then, and then. . . ." And they would always say: "But there's not enough bandwidth!" I never knew what bandwidth was, and I probably don't really know today, but I just knew that they were wrong—that it wasn't going to matter about the bandwidth. It was amazing to me: These guys were so smart, so technical. They were doing this stuff, but they couldn't see its potential.

How do you think computer media are affecting our unconscious minds? Do you think that affects people's creativity for either good or bad?
It must be having amazing effects on younger people, and I'm sure that it's having amazing effects on me, I'm just not sure what they are. Think of the people on, say, something like LiveJournal, who are totally exposing themselves to their friends, who are like 22 years old, and they don't know any different, and where is that going to go? Where is that going to go when those people start writing more novels? It's going to be different. I think that maybe with what I've done with writing these very speculative novels of the very recent past, I may be able to sit down and try to look at MySpace and all of that and see where it feels like that goes. Although I don't know; it may be too generationally specific.

Do you see any positive trend in current society that gives you hope that if we can no longer live without the Matrix, we might live with it more as the character Neo does—we live with it but are not enslaved by it?
The Internet gives me hope that way every day. I think that's the big one for me. I think if we didn't have that, I can't even imagine where we would be now. To me, the Internet is as basic a thing for humanity to be doing as, say, cities have been. It's that primal, that important, maybe more so. I think it's a fundamentally new way of doing a lot of things that we've always done, and it's also such a fertile ground for so many things that we've never really done at all.

If you could build a little binary time-travel switch between 2007 and 1967, and you toggle back and forth, the biggest difference is the Internet. And it's one of the things that you just couldn't have imagined from 1967. That's a very interesting thought experiment, by the way. I recommend that to anyone: Sit down and choose a year—it doesn't have to be 1967, of course, but it only really works if you choose a year in your own life—and compare it to your sense of where the present is and look at the difference. What most people experience when they do that is vertigo. It scares them. They say, "Oh, it's really changed a lot," and suddenly feel like they ain't seen nothing yet.

Early on, you were fascinated by how people related to their machines. How do you see the relationship between man and machine progressing?
There's a blip of that in *Spook Country*, where they're sitting around in the coffee shop in Los Angeles and one of the virtual reality art people says, "Cyberspace turned itself inside out." By turning itself inside out, the digital has become the constant; it's becoming where we all are, all the time. And really the exotic and kind of weirdly unexplored area is the part of our lives that isn't online, that for some reason can't be online.

So in that sort of scenario, people might be in some ways personalizing and fetishizing their hardware. Think about it: You've got all this junk lying around that's got really neat pieces inside it that are capable of all sorts of things—you might as well try to get in there and see what it actually does. Otherwise, you're just living in this

+

kind of molded little corporate surface world, where they are giving you a pretty little box and you don't know what's inside. And the truth is, there's power inside.

FROM THE AUGUST 2007 ISSUE

Discover Interview: Director of Iraq's National Museum

The archaeologist talks about the loss of artifacts and why he fled his homeland.

By Andrew Lawler | Friday, August 03, 2007

RELATED TAGS: ARCHAEOLOGY

Uruk, located near Basra in Iraq, was one of the world's first cities, and it is where the first writing system emerged. Babylon, just an hour's taxi ride from Baghdad, was long the world's largest and most sophisticated urban center. And the first truly international empire was ruled from the great Assyrian cities of Nineveh and Nimrud, near today's Mosul in the northern part of the country.

The past four years of war and political turmoil have threatened that invaluable heritage—both above and under the ground. Donny George Youkhana, who chaired the Iraqi State Board of Antiquities, has been placed in jeopardy as well. The 56-year-old archaeologist has been vilified as a Baathist sympathizer by American neoconservatives, criticized as pro-West by Sunnis, and viewed with suspicion by Shiites because of his Christian background. "I never knew if I would make it to work," he says of his daily life in Baghdad since 2003. "Or if I would make it home." In 2006 he left Iraq, joining the ranks of more than 2 million Iraqis who have fled since 2003. Last November he accepted a teaching position at the State University of New York at Stony Brook. He is one of only a few hundred Iraqi refugees who have been admitted to the United States.

Sumerian bust of a Bearded Man circa 3500-3200 BC

Image courtesy of U.S. Department of State, Bureau of Educational and Cultural Affairs

Donny George, as he is known in the States, started his career in archaeology as a storeroom assistant at Iraq's National Museum, an institution that houses not only most of the artifacts excavated in Iraq during the past 150 years but also a vast store of knowledge on one of the first centers of civilization. Located in the center of Baghdad just off Haifa Street—now one of the most dangerous spots on the planet—the museum was founded in the 1920s by Gertrude Bell, an extraordinary British historian who helped draw Iraq's borders, choose its first king, and negotiate a peace among Mesopotamia's many clashing tribes.

Over the past three decades, George spent much of his time working on excavations in the field. Before the war, I accompanied him, along with some foreign archaeologists, to a site deep in the flat desert of southern Mesopotamia, where he was directing a dig at a buried 5,000-year-old Sumerian city. He talked of attending the weddings and funerals of the local tribe in order to win their trust and support in protecting the site. But when we arrived, he slung a rifle over his shoulder. During those hard years of economic sanctions, looters were already a danger.

George's foreign colleagues judged him among the best and brightest of Iraqi archaeologists. But what made him a virtual celebrity was his role in the aftermath of the April 2003 looting of the museum. U.S. Defense Secretary Donald Rumsfeld dismissed the melee with the memorable phrase "Stuff happens." While other antiquity officials avoided the media, George welcomed television cameras and print reporters to the museum grounds. His criticism of the U.S. failure to intervene helped turn the shocking event into a symbol of an invasion gone awry, and he traveled the world seeking financial and moral support for his battered institution. Although it turned out that most of the museum's priceless artifacts were safe, thousands of pieces are still -missing—a significant loss for any museum—and the search for them continues. Over time, George's diplomacy won the trust of the Americans in the Green Zone and also of the emerging Iraqi authorities: In 2004, he was put in charge of the Iraq Museum as well as the country's regional museums.

Meanwhile, the political tide in the capital began to turn. In 2006, a new Ministry of Tourism and Antiquities, staffed largely by members of the party led by fundamentalist Shiite cleric Moqtada al-Sadr, was set up to oversee the organization. George says the combination of professional frustration and a threat to his son's life made him take his family first to Syria, then to America. "I never wanted to leave the board—that was my life," he told me as we sat in the living room of his family's modest new home, just a few miles from the Stony Brook campus, where he is teaching Mesopotamian history and archaeology. On the mantel, lit by small tea candles, stood an image of Jesus and Mary.

With regard to the care of antiquities, how do you compare the Saddam era with the way things are today?
Saddam wanted projects to bolster his image, to show that he was a patron of history and antiquities, as were the ancient leaders of Iraq. Now, with the interference of new people who are illiterate about cultural heritage, everything is much more problematic.

Did you ever meet Saddam?
One time, when I was field director at Babylon. He arrived by car on September 21, 1987, stayed for two hours, and left by helicopter. We walked through the museum there, and he noticed an ancient inscription by King Nebuchadnezzar translated into Arabic and English. It mentioned that the king had been sent by the gods to serve and to lead the black-headed people. For some reason, Saddam told me the translation must be changed. I said, "No, this is a scientific translation, and we can't change it." He didn't say anything, but later a bodyguard grabbed me by the arm and asked how I could say no to the leader. Then he said, "Don't worry, you are safe."

The bricks in the Babylon reconstruction are stamped with Saddam's name. Whose idea was that?
This was his order, that we commemorate the reconstruction the same way that it was done in ancient Iraq, by some device such as stone monuments. The next day the written order came, and we put together a committee that decided that we stamp each brick with his name, and he approved that.

Did Saddam ever visit the Iraq Museum?
Only once, before he was president. He never came after that. That says to me he was not really interested in history and archaeology.

Did the Saddam regime interfere with your work?
We felt we had a good measure of independence as a scientific institution. There was never any interference when I was excavating or writing reports. But my contacts with foreigners were closely monitored. The one time it really hurt was when they formed a special team in 2003, before the invasion, to store safely the museum artifacts. I knew everything in the museum and had worked to store everything before the Gulf War in 1991. I think they were afraid, since I knew foreigners and was a Christian, that I would reveal the secret place where the material was stored. That really hurt.

How did you react after the museum had been looted?
I was angry. I knew it could have been prevented; I knew American forces were beside the museum and didn't do anything. It was a very, very big mistake that could have been prevented. Like most Iraqis, I thought the arrival of the Americans was very welcome, but when you work as an archaeologist for 30 years, love the field, and know each piece, and then you see all the destruction and looting—this was very hard. I can't support people who did not protect the museum. And I can't blame the soldiers—they didn't have orders.

What is the impact on Iraq as scientists and professionals like you leave?
I have seen hundreds like me leave. A good number, if they couldnot travel abroad, work in the north, in Kurdistan. But the result is a complete drain of good minds from Iraq. In 2003, there were big hopes people would come back and work.

How did the new Iraqi government handle antiquities?
In 2004, I was made director of museums, and from the start they started sending people loyal to al-Sadr's party to monitor and control everything in our institution. They interfered in every single thing and changed things without our knowledge. They encouraged the staff of the department to go directly to the ministry, rather than through us. They removed people not connected to the party and put people in who were not qualified. It is worse than under Saddam.

How is the new minister, who was appointed in 2006?
He's a dentist, and his wife—who is a member of the Parliament—is a relative of al-Sadr. I knew he knew nothing about antiquities, so I went to see him and explain how we work. After about 10 or 15 minutes, I realized there was a complete wall between him and me. He seemed to be listening but not following. I felt helpless. Afterward, he continued the same policy as his predecessor. He appointed one person without experience in manuscripts to be in charge of manuscripts. And the director of manuscripts was moved to the excavation department. It would be amazing if he even knew where Babylon was—it's not his field. I was by then chairman of the board, and I had the authority of a deputy minister. But I was given no authority over personnel or budget.

At the end, I found myself coming to work, sitting there, and doing nothing. The last straw was when I was told by the minister's adviser that I should look after myself. He said the al-Sadr party had given an order that since I was Christian, I should not be allowed to keep my job, that it was very important a Shiite Muslim have the position. I was shocked. I understood that if I stayed, they would fire me, or it would lead to problems or even assassination. That happens. A month or so later—the 30th of July—I applied for retirement. And the minister approved it immediately. Normally, a minister would call to find out the reason a senior official resigned, so it was clear he was waiting for me to quit. A week or so later we left Baghdad.

What is the status of the museum today? Is it threatened?

About three or four months before I left, we had a mass kidnapping take place in the street outside the museum. A dozen official cars painted in camouflage drove up, full of personnel who were completely armed, equipped, and wearing uniforms. They took 50 people off the street. Shortly after, the interior minister announced that they had nothing to do with the kidnapping. I immediately called my senior staff and asked one simple question: What can we do if these people come to the museum, accuse us of hiding something in our storerooms, and demand to go in? Can we stop them? We agreed there was no stopping them, so we started immediately securing the museum. We put antiquities in the registration rooms and labs into boxes, took them down into the storeroom, and started welding the iron doors. For a day and a half, we welded all the doors leading to the storerooms and to the museum area. And the last thing we did was to build a wall half a meter thick with bricks and concrete at the entrance. The museum was completely sealed. Now, unfortunately, the Ministry of Tourism and Antiquities wants to reopen the museum just to show the outside world Baghdad is OK and everything is fine. The museum director e-mailed me that she's under pressure to reopen. Of course it would be ridiculous to do this. [Since this interview, the tourism minister has been forced to resign, along with several other Shiite ministers. The museum remains closed.]

How bad is the looting in southern Iraq?

Last year, al-Sadr's followers attacked and burned the museum of Nasiriyah and its library. They said to the guards—and I know this is true because I spoke with them—"tell [local inspector] Abdul Amir Hamadan we will do to your antiquities exactly what the Taliban did!" In Najaf, al-Sadr's party was heard to tell worshippers that looting artifacts is ethical so long as the money goes for guns or building mosques. And we have started to have problems in an area in Basra called Zobeir—the original Basra—which was founded by the caliph Omar in A.D. 638. Our inspector says people are building houses on the site, in practice destroying the first Islamic city that was built outside the Arab peninsula. Historically, Omar is considered the enemy of all Shiites. So is it being destroyed intentionally or just neglected? I don't know. But I'm worried this is exactly what happened to the Samarra mosque and shrine [destroyed in a sectarian bombing in 2006]. This kind of conflict might also lead to huge destruction of Islamic monuments and archaeology. We have an armed force of 1,400 men to patrol the provinces, and we managed to get some cars from the State Department and about 45 cars from Unesco. We concentrated on Nasiriyah because the looting was so bad there and because there are over 700 archaeological sites in the area. Inspector Abdul Amir [Hamadan] and his team did a very good job, patrolling, arresting looters, and sending looted antiquities to the museum. But rich people on the city council with ties to the Islamic parties are agitating for easy access to antiquities.

Are archaeological sites in the north around Mosul—such as Nineveh and Nimrud—secure?

There are 1,600 sites in the Mosul area alone, but the situation is not as bad as it is in the south. The museum is safe; it's closed and there's no one there. People in the north and middle part of the country have always been much more educated, more careful with ancient sites, than the people in the south. It's not their fault. They were not educated and given what they need to live. In the late 1990s, I saw Iraqis starving in the south because of bad policies.

What was life like, living in Baghdad as a high-profile official and a Christian with ties to Americans?

I would drive to work with different cars—mine, my son's, the department's. I didn't want bodyguards because they draw attention. One day I would leave at 7 a.m. and another day at 10 a.m. Once home, I never went out after 4 or 5 p.m. In the last weeks, when the doorbell rang after dark, I'd grab my gun—I always had it at the ready. People are known to rush in and kill families, and I was worried this would happen to us. Even in the museum, guards and secretaries would check everyone coming to see me and turn away anyone we didn't know.

Do you see a way out of the mess that is Iraq today?

The situation now is that the Iranians are fighting the Americans in the south, Saddam's allies are fighting the Americans in Baghdad, and the militias are all fighting each other for power. I always say I'm not a politician, but everything can be solved by politics rather than force. The problems can be dealt with immediately if the Americans sit down with the Syrians, the Saudis, and the Iranians. In the end, you always have people sitting in a room with each other.

FROM THE SEPTEMBER 2007 ISSUE

Why Has Steven Pinker Studied Verbs for 20 Years?

The rules of language may reveal how our brains really work.

By Marion Long | Monday, September 17, 2007

RELATED TAGS: LEARNING

Fifty-three-year-old Steven Pinker may look like a rock star, but he is actually a linguistics explorer, hunting around the sentences and syntax of human language for clues (he calls them "rabbit holes") to the inner world of the human brain. His favorite rabbit hole is verbs—what they mean, how they are used in sentences, and how, according to his latest book, *The Stuff of Thought*, kids "figure it all out." Why so much attention to verbs? Pinker confesses in part it's simply because he finds them fascinating. As one of his colleagues remarked, "They really are your little friends, aren't they?"

For more than a quarter century, Pinker has been a driving force in linguistics theory, analyzing language in labs at MIT, Stanford University, and Harvard University, where he is currently the Johnstone Family Professor of Psychology. At MIT he studied colleague Noam Chomsky's theory of an "innate grammar," testing to what extent language is biologically programmed. His research suggests that language is an instinct, an evolutionary adaptation that is partly hardwired into our brains and partly learned. This work led Pinker to develop his theory of the evolution of the mind and the source of language. He wrote about his work in four popular books: *The Language Instinct* (1994), *How the Mind Works* (1997), *Words and Rules* (1999), and *The Blank Slate* (2002). Although his books present scientific research, they have twice been finalists for the Pulitzer Prize in part because they're so much fun to read, with Pinker's creative weaving of movie dialogue, snippets from novels, news headlines, Yiddishisms, even bits from comic strips.

In his books Pinker argues that the brain at birth is not simply a blank slate to be shaped by culture and experience. Rather, it comes programmed with many behavioral dispositions and talents. In other words, human nature is to some extent innate and shaped by natural selection. Not surprisingly, Pinker's ideas have been at the center of some heated debates, most notably a recent controversy at Harvard, in which university president Lawrence Summers offered innate gender differences as a possible explanation for the dearth of women in the sciences.

In many ways, Pinker's book *The Stuff of Thought: Language as a Window Into Human Nature*, which will be published this month, may be his most ambitious yet—an attempt to show that the entire range of human thought is built on the "scaffolding" of a few core concepts that shape our understanding of the physical and social worlds and form the basis for the way we interpret reality. We spoke with the researcher from his office in William James Hall at Harvard.

You've said that when you were growing up in the Jewish community in Montreal, you were surrounded by fervent devotees of all kinds of political philosophies, by passionate wars of language and ideas. Does this influence your efforts now to describe the universal patterns of thought underlying language?

Certainly the argumentative intellectual community that I came from got me interested in these large issues of human nature, which I really think made me interested in the human mind. But I definitely wanted to study it in a way that was more tractable than just arguments around the dining room table. So I went into cognitive psychology.

In your best-selling book *The Blank Slate*, you argue that the infant mind is not an empty vessel that society can fill with whatever values and behaviors it chooses but rather that we are born with predispositions that are genetically determined. Why do you think these ideas are so controversial?

I think there are a number of reasons that looking at human beings as biological organisms can be unsettling. One of them is the possibility of inequality. If human nature is a "blank slate," then by definition we're all the same. Whereas if nature endows us with anything, then some people might be endowed with more of it than others are, or with different stuff than others are. And people who are worried about racial discrimination or class discrimination or sexism would prefer that the mind be a blank slate, because then it's impossible by definition for, say, men to be significantly different from women. My response is that we shouldn't confuse our political and moral position that people should be treated as individuals rather than prejudging them as a member of a category—a political policy that I think worth upholding—with the empirical claim that all people are biologically indistinguishable or that the mind at birth is a blank slate.

The second fear, I think, is that of dashing the dream of the perfectibility of humankind. If we were all blank slates, we could change what gets written on children's slates and mold them into the kind of people we want. If people are born with certain drives, if certain ignoble traits, such as violence and selfishness, are innate, then that might make them unchangeable, and attempts at social reform and human improvement might be proven to be a waste of time. And there, too, my response is that what you find is that the mind is a complicated system of many parts, and there is room for social improvement in trying to get some parts of the mind to work against the others. For example, the frontal lobes, with their ability to empathize and to anticipate consequences of choices in the future, can override whatever selfish or antisocial urges may also be harbored in the brain.

A third fear is the fear of determinism, of a loss of personal responsibility. It's the fear that personal responsibility will vanish if free will is shown to be an illusion. And here, too, these fearful reactions are a kind of non sequitur. Because even if there's no such thing as a soul that's separate from the brain and that somehow pushes the buttons of behavior—even if we are nothing but our brains—it's undoubtedly true that there are parts of the brain that are responsive to the potential consequences of our actions, that are responsive to social norms, to reward, punishment, credit, and blame.

In your latest book, The Stuff of Thought, you discuss cursing and note that, in America, "the seven words you can't say on television" have to do with sex and excretion. In other parts of the world, other types of words are more powerful, such as ones drawn from religion.

Yes, it's particularly noticeable to someone like me who comes from Quebec, where the worst thing that you can say to someone is "Goddamn chalice." That really brings it home for me. We do have a trace of that in swear words like "hell" and "damn" and "Goddamn," but they've really lost their sting, and it has to be related to the fact that religion has lost its power over many people.

I think the reason that swearing is both so offensive and so attractive is that it is a way to push people's emotional buttons, and especially their negative emotional buttons. Because words soak up emotional connotations and are processed involuntarily by the listener, you can't will yourself not to treat the word in terms of what it means. You can't hear a word and just hear it as raw sound; it always evokes an associated meaning and emotion in the brain. So I think that words give us a little probe into other people's brains. We can press someone's emotional buttons anytime we want.

And there's an additional layer, which would account for the fact that the content of swearing varies across history and from culture to culture. The common denominator is some kind of negative emotion, but the culture and time will determine which negative emotion is commonly provoked, whether it's disgust at bodily secretions, or dread of deities, or repugnance at sexual perversions. The second, additional layer is that you recognize that the other person is evoking—and is intentionally evoking—that negative emotion, and you know that he knows that you know that he is trying to evoke it. That's part of why it offends you. And that's why the choice of word matters, as well as what the word refers to—why "the F word" is obscene, but "copulate" is not, even though they refer to the same thing. But you know when someone uses "copulate," they're referring to copulation, whereas when they use the F word, they are trying to get a rise out of you. So there again you get to the pragmatics as well as the semantics.

You say that in studying certain aspects of how children acquire language—specifically, how they learn to use verbs—you fell, like Alice, down a rabbit hole into a hidden world where you viewed the deeper structures of cognition. What did you see in that wonderland beneath the surface of our language?

One very crucial rabbit hole involved figuring out how children learn to use simple verbs for putting things in places, verbs like fill, pour, load, or splash—verbs involving movement of something to somewhere. The problem was, how do you account for how a little kid, who has no prior knowledge of how a particular language works and who isn't going to get explicit lessons about how to use which words in which circumstances, figures out what words mean and what sentences they can be used in? We adults, for example, will say "Fill the glass with water" but not "Fill water into the glass," even though it's perfectly clear what that means. We will say "Pour water into the glass" but not "Pour the glass with water." And you know, "Pour the glass with water" is perfectly sensible, but it just doesn't sound quite right. But with a verb like load, we can say either "Load hay into the wagon" or "Load the wagon with hay." So you've got one verb that takes the container as the object, one that takes the stuff as the object, and the third that can go both ways. How do kids figure that out? Do they get it right to start with? The answer is no, not a hundred percent of the time. They do make some errors; they very occasionally say "Can I fill some salt into the shaker?" or "Stop pouring me with water." But the errors are fairly rare, and most of the time they use them correctly, and they grow up to be us, who use them correctly. What are they latching onto?

It turns out that they're latching onto different ways of framing the same situation. So if I go over to the sink and the faucet and the glass ends up full, I can think of that one activity either as doing something to the water (namely, causing it to go into the glass) or doing something to the glass (namely, causing it to change state from empty to full). That was the key insight to figure out why "fill" and "pour" behave differently.

If the simplest action, like putting some water into a glass, can be mentally framed in these two ways, with different consequences in terms of how we use words, that suggests that one of the key talents of the mind is framing a given situation in multiple ways and that a lot of insight into human thought, debate, disagreement, can come from thinking about the ways in which two different people—or one person at different times—can frame the same event. "Pouring water" versus "filling a glass" is a pretty mundane difference, but to speak of "invading Iraq" versus "liberating Iraq" or "confiscating earnings" versus "redistributing assets" would be more consequential. I think it illuminates the same aspect of our minds. This is a pervasive power of the mind; it's

+

seen in battles over perspective on all kinds of issues. It makes us capable of flip-flopping on a course of action, depending on how the action is described. It suggests limitations on our rationality—that we might, for example, be vulnerable to fallacies in reasoning or to corruption in our institutions.

Huey Newton, the cofounder of the Black Panther Party in the 1960s, once said, "Power is the ability to define phenomena." Isn't that right in line with many of your observations?
Yes, exactly. Although I would add that it doesn't mean that these debates are just about words. The words are means for trying to change people's minds, but there is something that you're trying to change their minds about. We're not just trapped in a world of language. Take "invading Iraq" versus "liberating Iraq"—those are different ways of framing the same military action, but there is a fact involved here as to which it is, and that depends on whether the majority of the population resented the former regime and welcomes the new one, or vice versa. So although you may choose one frame rather than the other in order to persuade people to believe the one thing rather than the other, that doesn't necessarily mean that one frame is as true or as good as the other. This continues my general theme: It's important to understand the great power of language, but one shouldn't overestimate it. One shouldn't think that we just live in a fantasy world of our own linguistic creations.

You say that language exposes our limitations, but you also insist that it can show us a way out of them. In fact, you have a linguistic superhero, don't you, in the reality of the metaphor?
Yes, I have two superheroes, actually. One of them is metaphor, the other combinatorics. Metaphor would be the way in which we transfer and transform ways of thinking that came from the realm of very concrete actions like pouring water or throwing rocks or closing a jammed drawer, and so on. But we can leach the content from them and use them as abstract structures to reason about other domains. We can talk about the economy rising and falling, as if it were a domain. We can use graphs to convey mathematical relationships as though they were lines and shapes drawn in space.

An enormous amount of scientific language is metaphorical. We talk about a genetic code, where code originally meant a cipher; we talk about the solar system model of the atom as though the atom were like a sun and moon and planets. And although we use these metaphors of concrete things to stand for abstract concepts, that doesn't keep us from putting a different twist on those same metaphors of the concrete and using them to describe other and quite different abstract concepts. When we put together the power of metaphor with the combinatorial nature of language and thought, we become able to create a virtually infinite number of ideas, even though we are equipped with a finite inventory of concepts and relations. I believe it is the mechanism that the mind uses to understand otherwise inaccessible abstract concepts. It may be how the mind evolved the ability to reason about abstract concepts such as chess or politics, which are not really concrete or physical and have no obvious relevance to reproduction and physical survival. It can also enable us—when we lose ourselves in the words of a skilled writer, for instance—to inhabit the consciousness of another person.

You argue that metaphor and combinatorics should be keys to our education, that we should be taught to think and to use language in a way that will promote our development and productivity. Why?
We must tap the mind's ability to grasp things in familiar ways and then to stretch them to apply to new ideas and areas of thought. But we also have to be mindful of the fact that there are ways in which any metaphor may or may not correspond accurately to the thing you're using it to explain. So just using or pointing out the metaphor isn't enough. To make it true and useful, one then has to add all these qualifications, like, well, yes

+

it's like this in one regard but not in another. So, for example, the mind is like a computer in that it depends on information storage, but it's not like a computer in that its accuracy isn't highly reliable and it doesn't work serially but rather in parallel. Or that natural selection is like a design engineer in the sense that parts of animals become engineered to accomplish certain things, but it is not like a design engineer in that it doesn't have long-term foresight. So the analogies in a metaphor can give with one hand but take with another. That is, it can give you insight but also lead to a lot of bogus conclusions if it's used carelessly. But surely metaphoric insights, the seeing of resemblances and connections, can give rise, and have given rise, to countless innovations in science, the arts, and many other fields of endeavor.

Yet don't you think that most education, and what most people believe education should be, is just the opposite of what you describe? Don't many people think it should be a kind of indoctrination in our society's conventional ideas?
An important key to doing that is to tap the little kernel of motivation to know the truth and not allow ourselves to be fooled or misled. That's there in everybody, somewhere. You don't like to be lied to, by your friends or in your business dealings. So why would you want to be lied to when it comes to the origin of life or the fate of the planet?

This built-in bias is something that has been established by social psychology, called a self-serving bias or what you might call the "Lake Wobegon effect" (you know, that's the place "where all the children are above average"). Well, a majority of people believe that they're above average in any positive trait, or if not themselves, then certainly the group that they belong to.

Is there a particular kind of scientific or intellectual inquiry that you're especially drawn to?
Yes. I get drawn in when I feel there is something deep and mysterious going on beneath the surface of something. I spent 20 years doing research on regular and irregular verbs, not because I'm an obsessive language lover but because it seemed to me that they tapped into a fundamental distinction in language processing, indeed in cognitive processing, between memory lookup and rule-driven computation.

It's intuition that tells me that, although I don't understand the thing yet, and even though I don't know what the answer is going to turn out to be, there's something big there—something important—that I won't be able to answer unless I understand a lot about the mind at a very deep level.

So my concentration on the choices of regular and irregular verbs was driven by my sense that it would reveal something about mental computation. The years that I spent studying verbs and what they mean involved a leap of intuition that this would be a way of tapping into human concepts and cognitive framing—in other words, the stuff of thought. That if you could really understand why the verb "fill" differs from the verb "pour," and both of them differ from the verb "load," you'd penetrate deeply into human thought patterns.

It's a rabbit hole phenomenon—namely, there's just a little opening, but there's something very rich and deep and important and mysterious, something big, going on down there, beneath the surface. And that lure has always governed which phenomenon I chose to explore.

+

FROM THE OCTOBER 2007 ISSUE

The Granddaddy of Space Colonization?

Fifty years after Sputnik, Burt Rutan leads a new space race.

By Jack Hitt | Monday, October 08, 2007

RELATED TAGS: SPACE FLIGHT, NEW PLANETS

Photo by Frank W. Ockenfels

If Burt Rutan ever read science fiction, he might recognize himself. A strong-willed, technically skilled, maverick spaceship builder with a healthy disdain for bureaucracy and a libertarian streak a mile wide, the 64-year-old Rutan could have stepped from the pages of a Robert Heinlein novel. Rutan first came to fame in 1986 as the revolutionary designer of Voyager, the first airplane to circle the globe nonstop without refueling. No fewer than six Rutan-designed craft are in the Smithsonian's aerospace collection, including his most famous design to date: *SpaceShipOne*. In 2004, *SpaceShipOne* was the first—and so far only—private manned spacecraft to fly above Earth's atmosphere in a suborbital arc.

Rutan, with his company Scaled Composites, is now trying to capitalize on the success of *SpaceShipOne* by building *SpaceShipTwo* for Virgin Galactic, a space tourism company founded by another famous maverick, Richard Branson. Virgin Galactic plans to offer well-heeled tourists short suborbital trips into space by 2009. Ticket prices for the ride have been set at $200,000 per passenger, and to date, about 200 people have bought seats.

Looking a little like a futuristic corporate jet, *SpaceShipTwo* will be almost three times as large as *SpaceShipOne*, featuring a roomy passenger cabin with seating for six and a two-person cockpit. But the basic design is the same as *SpaceShipOne*—launched from an airplane, a hybrid solid/liquid–fueled engine will send the spacecraft arcing above the atmosphere. As the craft begins to fall back to Earth, hinged segments of its wings will rotate until they are perpendicular to the rest of the wings, automatically forcing the vehicle into the correct attitude during reentry.

DISCOVER spoke to Burt Rutan about his inspiration for *SpaceShipOne*, what S**paceShipTwo** passengers can expect to get for their money, why the future of spaceflight doesn't belong to NASA—and the aftermath of a recent explosion at one of Rutan's test facilities during a test of rocket motor components that killed three people and severely injured three others.

SpaceShipOne is different from any other spacecraft ever flown. How did you come up with the design?

I was working at Edwards [Air Force Base in California] when [test pilot] Mike Adams was killed flying the X-15 there. He had instrument confusion and didn't line the vehicle up straight during reentry, and it broke up. I focused on that because if we're going to be flying members of the public, we need a generic solution to that sort of accident.

What is the future of NASA, given the rise of the private space travel industry?
NASA is using government money to try to do several things at once. It is trying to keep the shuttle flying, and every time it has an accident, it adds thousands more engineers and programmers who do more and more work. The more you fly, the more man-hours it takes to fly, rather than less. At the same time, NASA is trying to go out and develop something that can service the space station and also go to the moon and to Mars. This means we have a whole new generation of designers at NASA who are precluded from going out and looking for breakthroughs. They are forced into building a shuttle replacement using hardware from the '60s and '70s. They are using for the second-stage rocket engine essentially the same engine that was on the Saturn [upper stages], which is a very low-tech steel-cased engine. They do this because it would cost more to go out and invent something new, because to invent something new you have to try things that you don't know will work. They worry that if things don't work, Congress and the taxpayers may look at a failure as a waste of taxpayers' money rather than a normal thing that happens when you are doing research. That's why I don't feel inappropriate in pronouncing NASA naysay, because they are forced to do that.

Sometimes it seems as if NASA doesn't do anything right. Do you feel that way?
No, no. NASA does hundreds of wonderful things. They send robots all over the solar system. They have scientists doing all kinds of stuff. Some of it is good work. The stuff that JPL [the Jet Propulsion Laboratory in Pasadena, California] does is fabulous work.

People think I'm a NASA critic. That's not true. I'm just saying what they are doing on [the manned space program] is not looking for the breakthroughs that are needed. The breakthroughs are likely to come from folks who go out and try some new stuff.

But I have a tremendous amount of respect for what JPL does. NASA did some phenomenal research during the 1960s in response to [Yuri] Gagarin [the first cosmonaut], and very quickly we were driving cars and playing golf on the moon. That is something that made me very proud to be an American who sent taxpayer funds to *that* NASA.

How will private spaceflight succeed as an industry?
Not by making [private] spaceflight twice as safe as government spaceflight, or 10 times as safe, but 100 or 600 times as safe. By 1931, after a few years' experience of flying scheduled airlines, those planes were operating at roughly 600 times the safety of the space shuttle. I look at safety not in terms of fatalities per passenger-mile, but when you get in and close the door, what is the risk of dying on this flight? In 1931, for commercial airlines the risk was 1 in 33,000. For manned spacecraft it has been about 1 in 70. I believe that to have an expanding business that won't be hindered by people's fear of flying you have to be as safe as the airliners.

Is there a role for the FAA in maintaining safety in space, as the administration now has for airplane travel?
The current solution is to let people fly at their own risk. Show them the safety record for the spacecraft they are flying on and have them sign a waiver that says they know this is dangerous and that they are willing to take the risk. The FAA only gets involved when it comes to the people on the ground, the public who aren't choosing to be passengers. The FAA is obliged to enforce rules of operation so that people don't have something coming

through their roof and killing them. I don't believe that [the FAA's involvement should be so limited]—the problem is that spacelines will be much more at risk from a lethal liability climate than if they did have FAA approval on their spacecraft safety.

How does *SpaceShipTwo* compare with Russia's old *Soyuz* capsule, which has already carried five private passengers into space?
I couldn't compare it to a *Soyuz*. It's OK for a space tourist like Anousheh [Ansari, who visited the International Space Station in 2006] to go into orbit in a very small capsule with tiny windows and three people crammed in. Because there you can have a destination that's big and spacious. Ultimately there will be some really cool stuff, like a resort hotel in orbit. However, for the industry we're starting now, for suborbital flight, there is no destination, so the spacecraft you go up in has to be large and spacious. That's why *SpaceShipTwo* is much bigger than *SpaceShipOne*: It needs to be because you want those six people to be floating around and enjoying themselves.

What will a trip in *SpaceShipTwo* be like for a passenger?
Well, my job is not going to be running a spaceline or selling tickets or flying. My job is to build a spaceship that is affordable and safe enough to fly the public. We are working very hard to optimize the experience, because if you don't give people the best experience, they will go somewhere else for their spaceflight.

What do you mean by "optimize the experience" for the passenger?
I don't want to indicate everything that entails because we'd just as well let our competitors find out about it at the latest possible moment! But some of the things we have talked about are that the ships will be large with large windows. It will be a large cabin. The details on how that's done we will be proving in test flights. I wouldn't be surprised if at that time we discovered other features that would add to the experience.

Looking out the window, what would I see?
We will likely be flying downrange a couple of hundred miles instead of going straight up and down like we did with *SpaceShipOne*. So the view will depend on where you fly. The photographs of space taken by our astronauts have been published all over the place. But the eye is a much more dynamic mechanism than any camera or pictures. It's a more exciting view in person than looking at the photographs. Of course, I personally am sick and tired of hearing people talk like that: I want to see it myself!

How will passengers prepare for flight?
We will use the launcher [the airplane used to carry *SpaceShipTwo* to high altitude] to simulate the reentry. By doing a descending return [with *SpaceShipTwo* still attached to the launcher], we can actually expose the passengers to high reentry g-loads and also give them a real experience of what this gentle and slow buildup of g's during reentry is like.

I think during your day or two of training, you will likely go up in the launch airplane and do some floating around in the cabin. You'll do it in the same seats and windows in the cabin that you'll go up in. I think you'll be able to just show up at the spaceport and training facility two or three days before your flight.

Will passengers on *SpaceShipTwo* be able to take pictures?
I don't think you'll want to. I think there will likely be video cameras mounted in the cabin taking pictures of you. I say you won't want to take pictures because when you go to the Grand Canyon, you walk out to the

guardrail and look out there. You usually don't approach with your camera in the on position and walk up and take a picture. You usually see people enjoying it with the best lenses we have, which are our eyes. Then before leaving, you take some pictures so you can show your friends at home.

The problem with a suborbital spaceflight experience is that it is relatively short. You would certainly be taking snapshots if you were spending a couple of weeks in a resort hotel on orbit. But for suborbital flight I think it will be better if the pictures you see are pictures of you watching, documenting your experience. It's something that will be automatically done, rather than you fumbling with your camera.

What do you say to those who argue that what you're doing is not really contributing to space exploration, it's just providing expensive entertainment for the rich?
Look at personal computers or how the Internet grew: Something done for fun turned out to be as necessary as electricity and water. It's because creative people saw what was there and discovered a better use for it. I think we will find that if we reach our goal of flying 100,000 people in the first 10 or 12 years on *SpaceShipTwo*, along with others out there with their different spaceships, you are going to get some unforeseen creativity, someone who will figure out something as important as the Internet.

What are the most difficult technological bugs facing you in the development of *SpaceShipTwo*?
If I told you that, it would be very revealing to my competition! I would love it if Jeff Bezos [the founder of Amazon.com and Blue Origin, a rival spaceflight company] came out and told me the two most difficult things about developing his suborbital ship.

Do you have any advice for someone coming out of college who wants to design spacecraft?
I would say that you don't have to be stuck working for NASA anymore, and that is good news. When I got out of college, America built and flew into space five different launch systems in seven years. We're now talking 13 years to do one launch vehicle, and it's going to be based on hardware that is 30 and 40 years old. So my advice would be, let's just hope that there will be a bunch of companies like mine developing new rocket launchers, spaceships, and boosters, like we did in the '60s. I personally think there will be a lot of jobs.

Is there a private space race going on?
Of course there is; the biggest competitors are the Russians. Just like in 1961 with Gagarin, the Russians have beat us on the first salvo with Dennis Tito [the world's first space tourist]. Who would have thought in the 1960s that the first capitalists to sell tickets to let the public fly would be the damned Russians? Who would have thought that? Doesn't that piss you off? Well, we're going to do something about that.

Who are your competitors?
Virgin Galactic, which will be operating *SpaceShipTwo*, will be only one of several spacelines. The competitors for Virgin include the Russians, Bezos's Blue Origin, and possibly Rocketplane Kistler. And likely a couple of others who are smart enough not to tell people what they are doing!

What will spaceflight look like a century from now?
A century is a relatively short period of time. Let me stick my neck out a little bit further and say that in 300 or 400 years, a large majority of people will go to a planet and not return back to the Earth. We will colonize. Lewis and Clark went out and back. But most of the people who followed them went to California and stayed there. In a hundred years, I believe you will see such an enormous reduction in the costs of transportation

around our solar system that there will be a lot of travel. I'd like to see affordable transportation into space in my lifetime.

The Man Who Imagined Wormholes and Schooled Hawking

Kip Thorne revolutionized physics, fixed up Contact, and straddled the Cold War divide.

By Susan Kruglinski | Friday, November 09, 2007

RELATED TAGS: COSMOLOGY, STARS, DARK MATTER

Most people think of space as nothingness, the blank void between planets, stars, and galaxies. Kip Thorne, the Feynman Professor of Theoretical Physics at Caltech, has spent his life demonstrating otherwise. Space, from his perspective, is the oft-rumpled fabric of the universe. It bends, stretches, and squeezes as objects move through it and can even fold in on itself when faced with the extreme entities known as black holes. He calls this view the "warped side of the universe."

Strictly speaking, Thorne does not focus on space at all. He thinks instead of space-time, the blending of three spatial dimensions and the dimension of time described by Einstein's general relativity. Gravity distorts both aspects of space-time, and any dynamic event—the gentle spinning of a planet or the violent colliding of two black holes—sends out ripples of gravitational waves. Measuring the direction and force of these waves could teach us much about their origin, possibly even allowing us to study the explosive beginning of the universe itself. To that end, Thorne has spearheaded the construction of LIGO [Laser Interferometer Gravitational Wave Observatory], a $365 million gravitational-wave detector located at two sites: Louisiana and Washington State. LIGO's instruments are designed to detect passing gravitational waves by measuring minuscule expansions and contractions of space-time—warps as little as one-thousandth the diameter of a proton.

Despite the seriousness of his ideas, Thorne is also famous for placing playful bets with his longtime friend Stephen Hawking on questions about the nature of their favorite subject, black holes. Thorne spoke with

DISCOVER about his lifetime pursuit of science, which sometimes borders on sci-fi, and offers a preview of an upcoming collaboration with director Steven Spielberg that will bring aspects of his warped world to the big screen.

What does a black hole actually look like?

A big misconception is that a black hole is made of matter that has just been compacted to a very small size. That's not true. A black hole is made from warped space and time. It may have been created by an imploding star [where the gravity becomes so concentrated that nothing, not even light, can escape]. But the star's matter is destroyed at the hole's center, where space-time is infinitely warped. There's nothing left anywhere but warped space-time. A black hole really is an object with very rich structure, just like Earth has a rich structure of mountains, valleys, oceans, and so forth. Its warped space whirls around the central singularity like air in a tornado. It has time slowing as you approach the hole's edge, the so-called horizon, and then inside the horizon, time flows toward and into the singularity [the central spot of infinite density and zero volume], dragging everything that's inside the horizon forward in time to its destruction. Looking at a black hole from the outside, it will bend light rays that pass near it, and in this way it will distort images of the sky. You will see a dark spot where nothing can come through because the light rays are going down the hole. And around it you will see a bright ring of highly distorted images of the star field or whatever is behind it.

How sure are you about this model of a black hole? Could the picture be wrong?

It is a firm prediction from Einstein's general relativity laws. Gravitational waves will bring us exquisitely accurate maps of black holes—maps of their space-time. Those maps will make it crystal clear whether or not what we're dealing with are black holes as described by general relativity. It's extremely unlikely that they are anything else, but that's the exciting thing—we've been wrong before. We've had enormous surprises before.

Einstein thought of black holes as theoretical curiosities. Since no one has directly observed one, how do we know that black holes truly exist?

We see very strong evidence right at the center of our own galaxy. Astronomers have seen massive stars fall toward some central object and whip around it, like a comet around the sun, and fly back out. They have weighed that central object by measuring how strongly it whips stars around it. It turns out to have the same gravitational pull as approximately 3 million suns, and it is very dark—astronomers see only weak radio waves there. It almost certainly is a black hole. And when quasars [extremely bright, compact objects at the centers of some galaxies] were discovered in the early 1960s, it was obvious that the source of power had to be gravitational because even nuclear power, which powers the stars, is too inefficient. The idea that quasars are powered by the accretion of matter onto black holes was proposed within months after the discovery of quasars. This was a huge change of people's views of the universe, and it came very quickly. There followed a period of rapid research, and by the mid-1970s we came to understand that black holes are dynamic objects with a rich set of properties. They spin, and they can vibrate.

What are the latest discoveries about black holes?

The most exciting things to me are the first supercomputer simulations of two black holes that spiral together and then collide, triggering wild vibrations of their warped space and time. There's a fascinating recent simulation by a group led by Manuela Campanelli and Carlos Lousto, who are now at the Rochester Institute of Technology, in which the two holes are spinning with their axes pointed in opposite directions in the plane of their orbit. As they come together, the whirling space around each hole grabs hold of the other hole and throws it upward, just before they collide. The merged hole flies upward from where the collision occurred, vibrating wildly, and fires a burst of gravitational waves in the opposite direction in order to conserve total momentum. It's similar to how a smoke ring propels itself forward through air.

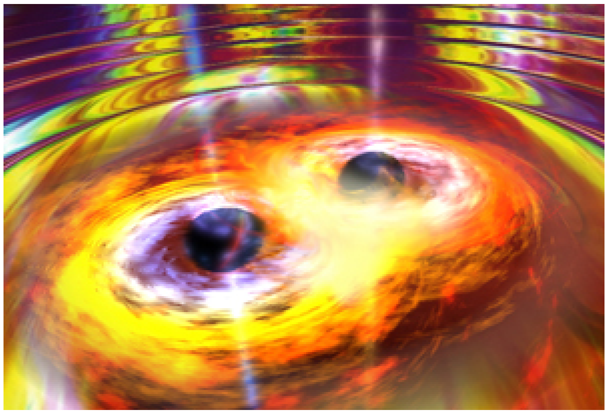


Image courtesy of Dana Berry/NASA

How soon might we see hard evidence of gravitational waves from violent events like colliding black holes?

LIGO is a several-stage project. We upgrade the detectors to better and better sensitivity. We are now operating our first detectors, completing the first long search. It's possible, but not probable, that we already have gravitational waves in the can, that we will see them as we complete the data analysis. In Advanced LIGO, which will begin its searches early in the coming decade, we expect to see a rich plethora of different types of waves, with signals coming in every day or week.

Can you describe briefly how you are going to be able to detect gravitational waves?

When gravitational waves reach the earth, the waves stretch and squeeze space. This is a tiny stretch and squeeze. Far too small to detect with ordinary human senses. We are attempting to detect the gravitational waves by hanging two huge mirrors from wires, each pair of mirrors about two and a half miles apart, and as the waves pass, the mirrors ride on that stretching and squeezing space so they are pushed apart and pulled together, back and forth. We monitor the oscillating separation between the mirrors using a laser beam. Even though these are 25-pound mirrors, their motions are so exquisitely small that they are perturbed quantum-mechanically by our monitoring. And so we have had to devise ways to get a gravity wave signal into these mirrors and through them, without it being contaminated by the quantum jiggling motion of the mirrors. Normally, you only see quantum-mechanical jiggling when you look at objects the size of atoms and molecules, but we are moving into a domain where we see the centers of mass of these big mirrors jiggle quantum-mechanically. We will soon be measuring the motions of the mirrors with a precision that is about the same as the width of the mirrors' quantum-mechanical wave function, which means that we will see the mirrors behave quantum-mechanically. We will see these human-sized objects behave like atoms behave and molecules behave, which has never, ever been done before.

How is this possible?

My superb experimentalist colleagues are able to do it because they are making such exquisitely accurate measurements. The motions that they are now able to see are at a level of about 1/100,000,000 the size of an atom. The surfaces of the mirrors have bumps and valleys that are the size of a few atoms. And we're measuring them to an accuracy of almost a billionth of the size of the bumps and valleys. And so you might say: How is it possible to measure that level? The answer is the laser beam is big—something like four inches across—and it averages over huge, huge numbers of these bumps and valleys, and it averages over time. We're looking for the motion of the centers of the mirrors as they move back and forth about 100 times a second. But the atoms inside the surface of the mirror are oscillating thermally at somewhere around one trillion oscillation per second. So, we average over an enormous number of thermal oscillations and an enormous numbers of atoms—the laser beam does that automatically. And it thereby can actually be sensitive only to the exquisitely tiny average motion of the whole mirror, the so-called center of mass motion.

+

Besides black holes, what other kinds of objects that are made from warped space-time and create gravity waves?

Well, a neutron star is an example. It's made partially from nuclear matter and partially from warped space and time. We hope to watch a black hole tear a neutron star apart. We will see the dynamical behavior of the warped space and time around these two objects as one destroys the other. Another example is something called a cosmic string. These are hypothetical cracks in the fabric of space that are thought to have been created at the very beginning of the universe, by the inflationary expansion of fundamental strings—the objects that string theorists tell us everything is made from. Cosmic strings are like cracks in the fabric of space. The geometry around a string is not like that of a flat sheet paper. Instead, space is warped in a conical sort of a way; the circumference around the string is less than pi times diameter. The core of the string is made of fields that have enormous energy that do this warping, and the core has enormous tension, like the tension of a violin string. If you pluck a violin string, waves go traveling along it. Similarly if a cosmic string gets plucked, oscillations travel along it at very high speed—at the speed of light—and they produce gravitational waves as they travel.

Cosmic strings are an idea that comes from string theory, the most studied area of theoretical physics. This area is still a long way from being a coherent unification of quantum and classical physics. Do you think string theory is exciting enough to merit the amount of attention it's gotten?

Absolutely. I think there's no question. It shows many signs of being on the right track toward a correct quantum theory of gravity. It has given rise to a number of very important ideas that have a good shot at being correct, such as higher dimensions, such as the possibility of forming mini-black holes at the LHC [Large Hadron Collider, a new particle accelerator that may be up and running next year], and thereby probing higher dimensions. String theory is now beginning to make concrete, observational predictions which will be tested. Claims that it is just theorists playing mental masturbation are, I think, nonsense.

What about those mini-black holes that may be produced by the LHC. How do they relate to the black holes that you study?

The black holes that we study as astrophysicists are huge, and they have enormous gravitational pulls. The mini-black holes that might be formed at the Large Hadron Collider are radically different from those huge astrophysical holes. It's unfortunate that they have the same name because it's like saying that a human being and an amoeba are the same entity, and giving them the same name because they are living things made out of matter. The black holes that one might see at the LHC are in some sense very distant cousins of huge astrophysical holes, with radically different properties. We will see mini-black holes only if our universe has higher dimensions, and then only if they form and evaporate through what's called Hawking radiation [a kind of radiation that is hypothesized to escape right along the horizon of a black hole]. A large fraction of the evaporation products go off into the higher dimensions, and so here we are exploring a very different aspect of the warped side of the universe, the influence of higher dimensions. If evidence is seen in the LHC for these mini-black holes, it'll be convincing evidence of the existence of higher dimensions.

What are some of the big surprises from your lifetime of studying theoretical astrophysics?

Oh, I think the biggest surprise to me was the discovery of dark energy; that most of the mass in the universe is in the form of this dark energy that extends throughout the universe, and has an enormous tension like an exceedingly stiff rubber band. That I found incredible. I and most of my colleagues didn't believe it until we saw several completely independent pieces of observational data saying that that's the case.

From the 1960s through the 1980s, you collaborated quite a bit with Russian physicists. What was it like to work with them during the cold war?

I managed to do this in large part because a Russian astrophysicist named Yakov Zel'dovich took me under his wing. He and Andrei Sakharov had been the principal designers of the hydrogen bomb in Russia. John Wheeler, one of the designers of the American hydrogen bomb, was my Ph.D. thesis adviser, so I was personally close to the designers of both the Russian and U.S. hydrogen bombs. I moved freely back and forth between Russia and the United States as an intellectual gadfly, carrying astrophysics and relativity ideas back and forth and helping the two sets of scientists communicate with each other.

Were you watched and questioned by government agents?

I was pretty sure that the CIA or FBI was bugging my telephone occasionally here in the United States, but they never came to me directly. After I would leave the U.S.S.R., my Russian colleagues were typically debriefed by the KGB about what had happened during my visit. The monitoring was much more intense on the Soviet side. The KGB often tried to use Russian scientists as spies, and this was a painful issue that some of my Russian colleagues had to struggle with. The CIA never, ever tried to use me as a spy.

Science fiction fans love you because in the 1980s you suggested that time travel might be possible by passing through a thing called a wormhole. How would that work?

A wormhole is a hypothetical warp of space that can serve as a shortcut between two different regions of the universe. It's sort of like if a worm drilled a hole through an apple from one side to the other. If you were an ant and you lived on the surface of the apple, there could be two routes to get from one side of the apple to the other. One is around the outside, on the surface, which we can think of as being like our universe's gently warped space; the other is down the wormhole. In the case of our universe, the wormhole might be quite short and still reach from, say, our solar system to the center of our galaxy. General relativity says wormholes could exist. When we combine general relativity with quantum theory, we find moderately strong evidence that wormholes cannot exist after all—but we just don't know for sure yet.

How did wormholes lead to your interest in time travel?

In Carl Sagan's original version of his novel *Contact*, he had his heroine traveling through a black hole to a distant part of the universe, and he asked me for advice. I immediately told him, "You can't do that. Black holes can't be used in that way," and I suggested he use a wormhole instead. That got me interested in the issue of whether or not there really could be wormholes that you could travel through, and quite quickly I came to realize that if they did exist, it would not be hard for a very advanced civilization to use a traversable wormhole to make a time machine. That forced me to face the issue of self-inconsistent histories: Could you go back and kill your father before you were conceived? And that question led me to realize that these kinds of thought experiments can be a very powerful way to probe the laws of physics. I had friends who worried about whether I'd gone off the deep end when they first heard about this, but most became enthusiastic after they learned the details.

Could it really be possible to travel backward in time?

It's quite unlikely that one can go backward in time—although it is certainly not ruled out—and it may be that nature has mechanisms to prevent backward time travel. When I was studying this, I came away convinced that the laws of physics can be readily adapted to backward time travel without any serious loss of ability to predict and without self-inconsistencies. I think more interesting was the discovery I made with a postdoc, Sung-Won Kim from Korea, that there is a universal mechanism that always occurs: If any highly advanced civilization attempts to make a time machine for backward time travel, quantum effects will cause the time machine to begin to self-destruct explosively at the moment you activate it. We don't know whether the explosion is strong enough to always destroy the time machine. We will have to have in our hands the full quantum theory of gravity [a combination of general relativity and quantum mechanics, yet to be understood] to find out the answer.

This kind of research certainly hasn't hurt your career. Carl Sagan, on the other hand, did have to deal with a backlash because he was writing fiction and thinking about extraterrestrial civilizations. You were friends with him. Did this backlash really damage his career?
He had some backlash to deal with, but I don't think it hurt his career among his immediate colleagues. He was elected to the National Academy of Sciences and then his election got quashed in the final meeting, when it should have gone through. It was quashed by people who were not close to his field. I think that was typically true, that his immediate colleagues—those who had worked with him, those who knew his research from having read his papers—they had high respect for his scientific work. It was people who had little personal knowledge of his research, who were the cause of whatever problems he had.

There is a rumor that you are working on a sci-fi project with Steven Spielberg. True?
I'm working on a science fiction film with Steven that's based on a treatment I coauthored with the producer Lynda Obst. I will be an executive producer on the film, basically focused on bringing good science into it. I expect that nothing in the film will violate fundamental physical law, and all the wild speculations in the film will spring from science. The working title is *Interstellar*, but it's unlikely that will be the final title. It is a story in which the warped side of the universe plays a major role.

Can you describe some of the bets you've had with Stephen Hawking—and who won?
Our first bet was about Cygnus X-1, the first strong candidate for a black hole that anyone had found. Is it really a black hole? Hawking characterized that bet as his insurance policy because he had so much invested in it turning out to be a black hole, so he bet against his hopes. He figured if it turned out not to be a black hole, he at least would get something out of the disappointment. The bet was very nonpolitically correct: He gave me a subscription to Penthouse magazine when I won. We also had another bet: John Preskill and I on one side—Preskill's a physicist at Caltech—and Hawking on the other. The bet was over whether the laws of nature permit an implosion to produce a naked singularity—a singularity that is not inside a black hole. We bet that it could, and Hawking bet it couldn't. He had to concede when a naked singularity was actually created in a finely tuned implosion, simulated on a computer. Now we have a new bet over whether a naked singularity could occur naturally in the universe.

What did you win on that second bet?
The loser had to give the winner an item of clothing to hide the winner's nakedness. Hawking conceded in a public lecture at Caltech, and he had his assistant present to us T-shirts that had a picture of a woman hiding her nakedness with a towel. On the towel was written "Nature Abhors Naked Singularities."

You also placed a wager on one of the strangest ideas about black holes: Not only do they swallow matter and light, they even obliterate any clues or information about the event. What was the argument in this case?
If you have something that implodes to make a black hole, which then completely evaporates due to Hawking radiation, does all the information that went into the black hole come back out? The fundamental principles

quantum theory say yes, and Preskill took their side. General relativity seems to say no, and that's the side that Stephen and I took. About three years ago, Stephen found a new way to analyze the evaporation process, a way that convinced him that Preskill was right and that the information could be recovered, in principle. Hawking conceded in a big ceremony at an international meeting in Dublin where I was the chair. But I haven't conceded yet.

And that was for encyclopedias?
That's right. The loser was to provide the winner with an encyclopedia of information. So Stephen gave John, who has a fabulous collection of these baseball cards, an encyclopedia of American baseball.

It sounds like Hawking hasn't done very well in his bets.
He hasn't won any of these bets yet. I think that characterizes the fact that he's ready to go out on a limb and challenge people, as a way of trying to foster the forward movement of science.

Are you still in contact professionally with Hawking?
He and I have never written a paper together. His current focus is the birth of the universe. Mine is probing its warped side. I will be going to Cambridge soon and spend a day with him, and we'll be talking about physics and about life. He's just finished writing a book for children called *George's Secret Key to the Universe*. I'm eager to read it. It should contain gems of wisdom, not just for children but for adults and probably also for physicists like me.

FROM THE FEBRUARY 2008 ISSUE

A Chat With George W. Bush's Conscience

Embryonic stem cells crashed against Leon Kass' old-school moralism.

By Francis Wilkinson | Wednesday, February 20, 2008

RELATED TAGS: HEALTH POLICY, BIOTECHNOLOGY, FAMILY HEALTH, PHARMACEUTICALS

As a former chairman of George W. Bush's President's Council on Bioethics, Leon Kass is well acquainted with controversy, and with the treacherous terrain at the nexus of science and politics. The council, tasked with advising the president on such hot-button issues as stem cell research and cloning, has sometimes been dismissed as a vehicle for the right wing of the Republican Party. But although some of his views comport with those of hard-liners, Kass, a physician with a Ph.D. in biochemistry, is hard to pigeonhole. "I do not come from a school of thought, nor do I have an ideology," he says.

An old-fashioned moralist, he holds some views that are remarkably unfashionable—even premodern. He still employs the term *bastard* to describe the children of unwed parents, and he has written despairingly about the loss of "female modesty" in our culture. At the same time, he has misgivings about the effects of global capitalism and believes in integration, tolerance, and inclusiveness. In the end, what really rankles many scientists is Kass's belief that society has a duty to regulate research, and his frequent warnings about the dehumanizing effects of some technologies.

The recommendations of the Council on Bioethics, though substantive and scholarly, have by and large not been put into practice by policymakers, and the group's prominence has faded as the debate about stem cell research has ground to a standoff. Kass left the council in September and currently is a fellow at the conservative American Enterprise Institute for Public Policy Research, where his office is a few paces from Lynne Cheney's. He sat down with DISCOVER to reflect on his tenure and discuss his beliefs, his influences, and his concerns for the future.

You were chairman of the Council on Bioethics, yet you don't regard yourself as an ethicist. Why?
I do not present myself as having professional ethics expertise, the existence of which, in fact, I have doubts about. The term *ethicist* is of recent vintage. I prefer to say that I engage in moral reflection on various matters of human experience but look at them not through the lens of any ethical theory or system. I'm an old-fashioned humanist. A humanist is concerned broadly with all aspects of human life, not just the ethical.

How did you develop this perspective?
My parents were one of my major influences. Both were immigrants from Eastern Europe with no formal schooling. My father had a clothing business on the South Side of Chicago. My mother read novels late into the night. It was a Yiddish-speaking, secular, socialist-leaning home, like lots of others around that time, but with a very strong emphasis on doing the right thing and being a mensch. Moral questions were discussed around the dinner table.

I was an early protester against the Vietnam War. I was probably something of a peacenik. My wife and I did civil rights work in Mississippi when I was still in graduate school at Harvard. And I came back with this question: Why was there more honor among these poor black farmers in Mississippi than among my fellow graduate students at Harvard? The answer seemed to me to have something to do with their religious faith.

A question you're currently taking on is how we should deal with progress and technology.
I think lots of things conspire against dealing in a sensible way with technological advance. There's a large cultural bias toward progress, a belief that innovation is good innovation. We love the freedom of scientists to inquire, of technologists to invent, of entrepreneurs to develop, and of customers to buy what they want. The country runs on this principle. I'm inclined to a more classically tragic view in the sense that all the good comes with some bad. We pay a price for everything. And you pay a higher price if you don't know that you pay a price. In the biomedical area, the people who are bringing you all the novelties occupy the moral high ground. They are humanitarians. They are interested in curing disease, ending suffering, extending life. If anybody says, "Let's go slow here," it looks like the imposition of a narrow religious view on what is a pluralistic society, and the response is "Get your morals off my science."

What about the commercial pressures of innovation?
Some of my old friends in the sciences are very worried about the biotech companies and how their intrusion into academic science skews the agenda. The commercial interests that are in favor of pushing the envelope are very, very well established. And there are no economic interests in favor of going slow. In Europe in the aftermath of the Holocaust, the concern for human dignity became embodied in the law. Americans, by and large, fly the banner of liberty and equality. We don't have the public language—other than religiously formulated language—for dealing with some of these things.

Are there any innovations you think should be prohibited?
I'm in favor of legislative bans on only a couple of things. Because the evils are so intimately connected with the goods, you don't want to kill the goose that lays the golden egg. But I would ban human cloning. And I would keep physician-assisted suicide and euthanasia illegal.

What else troubles you about contemporary medical research?
For my money, the area where we should be most concerned is psychopharmacology and the uses that go beyond treatment for clear psychiatric disorders—the whole family of mood-altering, euphoriant drugs that separate satisfaction from the human activities generally responsible for our achieving satisfaction. This is not puritanism on my part. I'm concerned about a society in which people refuse to take responsibility for themselves, about a society in which human aspirations are short-circuited because achieving them is too difficult and too painful. We're treating grief as a problem to be solved.

What about people who have endured horrible traumas? Shouldn't they be allowed to suppress their bad memories with drugs?
I have absolute sympathy for people who were in the World Trade Center or people who have experienced rape who want to have some way of blunting these memories to minimize the trauma. I'm all for doing this. But this is also going to foster the possibility of eliminating memories of acts that are shameful, acts in which we behave disgracefully, acts for which we should feel guilt and remorse and seek forgiveness. To sit as editor of our memories is to acquire a life other than the one we have truly lived, to fabricate an identity that is false to our lived experience.

You've raised concerns about the "medicalization" of society. But isn't it too late?
I taught my first bioethics course last spring. In several areas, the class did better than my council in seeing the dangers in the use of psychotropic drugs in children. There were several students who had been on Ritalin. And they spoke with subtlety about what it meant to be on this medication and how they differed from some of their friends who had toughed it out. I think most young people would like to be *really* happy rather than *appear* to be happy. Do they want the pleasure of hitting the baseball to come out of a bottle, without ever learning to hit the ball? No. They know the difference between excellence and mediocrity, and they want to feel the sense of their own accomplishment.

But you're not categorically opposed to the use of such drugs.
I'm not some sort of ogre who wants people to suffer for their own good. We learn sometimes when we suffer, but I don't approve of somehow increasing the amount of suffering in the world.

One of your most noted accomplishments as council chairman was the report "Reproduction and Responsibility." What were the council's goals in publishing that report?
There were certain boundaries we wanted to erect: no pregnancy except to give birth to a child; no human embryos placed in animals for any reason; no fertilization of a human egg by animal sperm or the reverse; no buying or selling or patenting of human life at any stage; no child conceived except by the union of one egg and one sperm, both taken from adults. The point is that no child conceived with the aid of assisted reproductive technologies should be denied the lineage and biological ties to two parents that all children born "naturally" have. No child should have to say, "An embryo was my father."

What kind of impact did that report have?
A few of our recommendations were enacted into law last year. The language was carefully worked out so as to satisfy both the pro-life and scientist members. We have shown a way to come together in defense of commonly held values, even while continuing to disagree on the moral status of human embryos. Our example, and the specific proposals, should be of interest to anyone wishing to overcome the current stalemate in Congress.

Why did stem cells become the dominant bioethical issue?
Stem cell research was everybody's Public Issue Number One—God knows, really, why. Partly as a legacy of the way the abortion decisions came about in this country and the degree to which abortion is important in American politics, killing and destruction-of-life questions have come to be regarded as the bioethical questions, whether it's euthanasia at the end of life or abortion and embryo destruction at the beginning.

Scientists recently announced that they have found a way to turn human skin into cells that have all the therapeutic potential of embryonic stem cells. How does that change the debate?
This is what everybody has been waiting for. They've hit a home run. One of the most popular things the council did was to suggest science could come to the rescue and find a way around an ethical impasse to produce a mode of obtaining stem cells that everybody would regard as ethical, and that this vexed period of our politics could be put behind us. This is just really quite thrilling.

The Bush administration has been accused repeatedly of injecting politics into science. Did you experience that?
We were not interfered with at any time. The president got a copy of the "Reproduction and Responsibility" report only the day before it went public, as a courtesy.

Another of the council's far-reaching reports is titled "Beyond Therapy." What's the difference between medical therapy and medical enhancement?
There is no bright line. But therapy, classically understood, is the removal of disease or disability and the restoration of health and normality. Enhancement would seem to go beyond the natural given powers, whether to increase IQ and memory or to boost athletic performance by steroids or by genetic modification of muscles. A number of questions are raised by this. First among them is, how do you know that the change is in fact a betterment? Nobody would question the correction of a cleft palate. On the other hand, there is the case of the surgeon who removed part of a woman's breast because it interfered with her golf swing. There is a distinction between serving the patient's health and serving the patient's desires. And there's a lot of gray area in between.

So are you opposed to plastic surgery?
I'd feel much better if they had some kind of body technicians who were not trained physicians to do this. It is a kind of corruption of the art to put it in service of satisfying people's desires—even when some of those desires are reasonable. I'm somewhat old-fashioned on that subject. If medicine is not guided by some kind of commitment to wholeness or healing, it's reduced to being a simple body shop where technicians for hire perform.

Are we too focused on personal happiness?
I think some of that is true. Families are more atomized. On the other hand, there is at least the recognition that we're in trouble. There's an enormous amount of work being done on what's come to be called civic engagement.

Religious institutions are part of that. Are you a believer?
I'm a member of a synagogue in Chicago. I don't really know the answer to this question.

That usually means no.
Well, take a simple aspect of it. Do I think there's an afterlife? I don't think I've spent five minutes of my life with that expectation. I'm agnostic on the question. However, I like the idea of living as if I'm going to have to answer for what I've done. I feel grateful. Do I know to whom or to what I feel grateful? I'm not sure. Am I aware that there are powers that move me in ways that are not at my disposal and under my control? Yes. Do I think there is an old man upstairs with a long beard who takes calls from room service? No.

What are the most significant bioethical issues of the future?
One of them is the large question of the health-care system. It's partly a bioethical topic. Some people put it in terms of justice. Some people put it in terms of rights to health care. My preference would be to say something along these lines: What does a decent and prosperous society owe to the health of its citizens? The crisis of ethical long-term care for the elderly might be the most important issue we took up in terms of how it affects the lives of pretty much all the families in the United States. Scientists hope for a magical cure of Alzheimer's. I have it in my family. It's depressing. Forty percent of us right now die after a period of enfeeblement, debility, and dementia lasting up to a decade. That's the most common trajectory toward death. In the more biotechnical areas, I think the possible hazards have to do with genetics. And pharmacology: Drug-induced pleasure or feelings of self-esteem are shadows divorced from the underlying human activities that are the essence of human flourishing. We want to feel good about ourselves, but only as a result of doing and being good.

Are you hopeful that people will voluntarily take that hard road to happiness rather than the easy way out?

I don't have any illusions about how easy it is to turn the culture around, but I've never had any dealing with any person who didn't have some aspiration to the good.

FROM THE APRIL 2008 ISSUE

From Haitian Zombie Poison to Inuit Knives Made of Feces

Wade Davis, a real-life Indiana Jones, chronicles cultures at the brink.

By Jessica Marshall | Thursday, March 27, 2008

RELATED TAGS: DRUGS & ADDICTION

Davis with Kofán shamans in Ecuador.

Image courtesy of Peter Von Putterkamer/ Gryphon Productions

On a break from college, Wade Davis, age 20 at the time, crossed the Darién Gap—the roadless, desolate, and dangerous 100-mile stretch of swamp that divides Central from South America. He was clueless, compassless, and on foot. And yet somehow he was chosen to be his group's guide.

His swagger certainly helped.

At 26 (and still alive), Davis entered graduate school under Harvard University's legendary Richard Evans Schultes in the field of ethnobotany, where he learned to search for new medicines from the plants that indigenous peoples use. But merely cataloging plants was not his style, so he applied for a doctoral dissertation grant to discover the recipe for zombie poison in Haiti. He got the grant—along with a note from the academic reviewers that said, "Davis must be told he will be killed if he tries to do this work."

In Haiti the swagger helped again. He won the locals' trust by drinking unidentified potions in a sorcerer's hut, winning impromptu horse races, and weaving luminous stories of that improbable land called Canada. He became probably the only white man ever to be initiated into Haiti's secret societies. And he got the recipe for zombie poison—part graveyard-snatched human bone, part buried toad, part toxic puffer fish, and more parts magic than an outsider had ever been willing to see.

His success brought instant fame. Davis stepped off the Haitian coast directly into a deal for what would become a best-selling book about voodoo culture, *The Serpent and the Rainbow*. Then he sold the movie rights, earning more money and becoming better known than the professors judging his work.

Ethnobotany's rock star returned to Harvard and got his Ph.D., but he turned away from academia just the same. "My forte was as a storyteller, grounded in the kind of training that I had in the academic world," he explains today.

In fact, for Davis botany was "a metaphor, a conduit to culture" itself. With the language of plants offering entrée to the people he found fascinating, he took off with rain forest nomads and wrote another book; he traveled with Inuit in the Arctic and wrote yet another.

In the course of his travels, he coined the term *ethnosphere* to describe the cultural web that encompasses the diverse dreams, myths, thoughts, products, and intuition of every culture on earth. Preserving that diversity is what Davis desires most. “Half the languages of the world are disappearing in this generation,” he says.

Davis does not consider preservation to be his job, however. “I’m not in the business of trying to save the Peruvian Indian farmer any more than he’s in the business of trying to save me,” he says. Instead, his goal is taking the rest of us to realms of cultural splendor so great that we will understand, finally, their value to the world. Toward that end he works full-time as explorer-in-residence for the National Geographic Society, holding perhaps the only job-with-benefits on par with astronaut for pure adventure and thrill. As a professional explorer, Davis travels the ethnosphere so he can discover and describe it in a stream of moving and popular exhibits, books, and films. His award-winning two-hour special for the History Channel, *Peyote to LSD: A Psychedelic Odyssey*, airs April 20, and the IMAX film *Grand Canyon Adventure*, made in collaboration with environmentalist Robert F. Kennedy Jr., premiered in March.

DISCOVER met with Davis in his Washington, D.C., home among the artifacts of his eclectic life: a tool for skinning the eyelids of wolves, a compound microscope, an upright piano, and an ornate wooden mask, carved in his likeness by an old Kwakiutl friend, who told him, “That’s your lips in old age, because you never shut up.”

When did you start exploring?

I was at Harvard in 1974, and Harvard was very intense in those days. I got there and I got very radicalized within about three days over the Vietnam War, so I spent most of my first year writing pamphlets and smashing windows, basically, and demonstrating. Then after a couple of years I was exhausted, and I was just gonna take some time off.

I was with my roommate, David, who was from a Montana ranch family. And we’re in a café in Harvard Square, and there was a National Geographic—ironically—map of the world right in front of us. And David looked at the map. We were downing a cup of tea or a beer or whatever it was. And he suddenly looked at me, and he looked at the map, and he pointed to the Arctic, and he looked at me. And I had to go somewhere, so I just—plunk—Amazon. And within two weeks he was in the Arctic, and he never came back. He’s still there. He lives in Alaska—I see him all the time. And in three weeks I was in the Amazon, where I stayed for a year and a half.

Having decided to go to the Amazon, there was only one man to see, and that was Richard Schultes, the Harvard professor who was the greatest Amazon explorer of the 20th century, without a doubt. So I knocked on his office door at Harvard. I just said: “Sir, I’m from British Columbia. I’ve saved up money in a logging camp. I want to go to the Amazon like you did and collect plants.”

Davis participating in a sacred Mazatec Indian "magic mushroom" ceremony in Oaxaca, Mexico

Image courtesy of Peter Von Putterkamer/ Gryphon Productions

At the time, I knew nothing of botany. I’d never taken a serious biology course—any biology course—in my life. And he didn’t ask for credentials. He just said, “Well, son, when do you want to go?” And two weeks later I was in the Amazon.

What advice did Schultes give you?
My poor mother. I was trying to placate my mother back in Victoria, so I went back to see him to get his advice and he said, "Don't bother with leather boots because all the snakes bite at the neck." And then he said, "Don't forget to bring a pith helmet." And then his third piece of advice was "don't come back without trying ayahuasca," which is the most potent of the hallucinogenic preparations of the whole shaman's repertoire.

Did you wear a pith helmet?
No

Get bitten by a snake?
No. I did step on an anaconda once. I never had any problems at all.

Did you try ayahuasca?
Oh yes, many times.

What is it like?
You are flung into other levels of reality so visceral, so tangible, so all-enveloping, that they become your sense of the real world. And you suddenly realize that the relatively mundane realm of ordinary consciousness is a crude facsimile of what awaits in the psychotropic trance. This and other experiences in the presence of people taken by the spirit left me with visceral evidence that cultural beliefs can really make for different human beings, that there are other ways of knowing, other levels of intuition, that cannot necessarily be understood through the filter of Cartesian logic.

What do you mean by "other ways of knowing"?
When Schultes was in the Amazon in the 1940s, the Seona in Ecuador identified for him 17 varieties of ayahuasca liana, and all of them, to his Harvard-trained taxonomic eye, were the same species. When he finally asked them to give him lessons in the nature of their systematics, they looked at him like he was a fool and said, "Don't you know anything about plants? Each one of these 17, when taken on the night of a full moon, will sing to you in a different key." That's not gonna get you a Ph.D. at Harvard, but it's more interesting than counting flower parts.

So drugs do for the Seona people what science does for us?
Not drugs. That's a pejorative notion in our society—cocaine, crack, crystal meth, whatever. These aren't drugs. These are sacred medicines. These are the facilitators. These are the avenues to the doorways of the gods.

You went from investigating one kind of sacred medicine to another. Is that what propelled you from the Amazon to Haiti?
I have always lived by the adage that if it works, it's obsolete. The minute I get good at something, I generally drop it and try something else. I was looking around for a thesis topic that would really catch me, and Schultes came up with this zombie thing. A team of psychopharmacologists led by a man named Nathan Kline—he was derided by one newspaper as the father of Thorazine, but his science was impeccable—went on record saying they had found the first zombie. They didn't believe in magic, but they believed it was possible that a person could appear to be dead in such a way as to fool a physician. The existence of a poison that would do that was taken for granted by the Haitian government and specifically mentioned in the penal code of the country, but

+

nobody had investigated to see what was in it. I went down there almost on a whim, thinking that the assignment would be a lark, a couple weeks in Haiti. In the end, of course, it consumed four years of my life.

How did you locate the zombie poison?
I was living in a stone hut on the beach and going out every night alone to these secret societies. When I went around the country, there was one consistent ingredient in these preparations, and that was these marine fish. I didn't know any of these fish from Adam, but I brought back all of the ingredients and the ichthyologist at Harvard identified them: puffer fish. He turned me on to this biomedical literature, and my God, I found case after case in which people had been nailed in their coffins by mistake. There was absolutely no doubt scientifically that these fish I had found in Haiti had, at least at certain times of the year, a drug in them, tetrodotoxin [TTX], that could make people appear dead. Haiti whacked me in the face like a sledgehammer. I remember that fantastic sense of how surreal Haiti was, a place of such poverty, where people adorn their lives with their imaginations. I didn't know it, but I had malaria and hepatitis at the same time. I felt like that line from the Bob Dylan song, "Something is happening here, but you don't know what it is, do you, Mister Jones?" Eventually a friend had to just pluck me out of Haiti and put me on her farm to write my book.

Why did you write a book before finishing your graduate thesis?
I walked in off the street in London and got a book advance. I used the book advance to pay for the research. Then I sold the rights to Hollywood—I wouldn't say naively, because I'd do it again today. I mean, name me a graduate student you know who would turn down a quarter-million dollars for the rights to their Ph.D. thesis—let's see them line up. It was a terrible movie. I risked a lot academically, intellectually, and personally to tell this story with honor and integrity, but it brought down all of this wrath.

People made some serious accusations against you at the time. What happened?

The minute those samples came back, Kao called me up and said: "You're all wrong. Get another thesis topic. This is nonsense."

And I said, "Dr. Kao, I told you that 50 percent of the time these fish are nontoxic. It varies tremendously, and it's highly significant that either sample showed any at all, because it means that tetrodotoxin was found. You also have to understand that the Haitian belief system allows a sorcerer an out, a way to rationalize failures and emphasize successes: *If I go down to the beach and give you a poison and absolutely nothing happens, I can say that my attempt to capture your soul was interrupted by a priest who protected you.* I explained all that to this guy, but he began writing hundreds of letters all around the country, unsolicited, saying, "I'm here to alert you to a serious case of fraud in science."

With all the uproar, I'm amazed you ever got your Ph.D.
When I wrote my thesis, Irvin DeVore, the greatest biological anthropologist in the history of the university, said it was the best Ph.D. he had ever read in his career at Harvard. But another professor involved in approval was overheard at a party after I was in *Time* magazine saying that no matter what happened, I would not get my degree.

And sure enough, when the time came around for the faculty to rubber-stamp the approval of the committee, that professor did not put the vote as an agenda item on this faculty board meeting. And in the meeting he suddenly stood up and started railing against my thesis, apparently. Fortunately one of my committee memb +

was there, this wonderfully kind botanist. So after this great tirade, Rolla Tryon just taps—in a classic sort of Harvard moment—taps his pipe on his glass of water and says, "Excuse me, but have you read the thesis?" And he had to admit that he had never seen it.

After all that, you abandoned the study of zombies. Why?

I was driving around Boston with this very close friend of mine, a professor of sociology. He looked at me—he had known me for years, and he just looked at me and said, "You know, Wade, do you want to be a zombiologist?" And it was like zazen from a Buddhist monk, because what he was really saying was: Here you are. You're in this whirlwind. Doonesbury was doing a three-week parody of the book. *Miami Vice* was doing episodes. I was on the Today show. It was completely surreal, right? And Charlie was saying to me, "Do you want to spend the rest of your fucking life defending this theory, running around Haiti trying to find more zombies?" And of course I instantly laughed and said no. And at that instant, I turned my back on the entire story. I never went back to Haiti, not out of any kind of bitterness or regret. I didn't want to be a zombie expert. Instead, I disappeared into the forests of Borneo.

Haiti, the Amazon, Borneo...How do you manage to fit in no matter where you are?

You're with a bunch of yak herders at night in Tibet, and you've got a choice: You can hang out with the other scientists and listen to their stories of Chicago or their problems with their wives, or you can just wrap yourself up in a blanket and go down and hang in the body pile with the yak herders and drink rakshi and eat tsampa and fart. I have a good intuition for finding that kind of opening into culture that allows you to be welcomed.

One of the cultures you celebrate in *Light at the Edge of the World* is the Inuit. What do you most admire about them?

The Inuit didn't fear the cold; they took advantage of it. During the 1950s the Canadian government forced the Inuit into settlements. A family from Arctic Bay told me this fantastic story of their grandfather who refused to go. The family, fearful for his life, took away all of his tools and all of his implements, thinking that would force him into the settlement. But instead, he just slipped out of an igloo on a cold Arctic night, pulled down his caribou and sealskin trousers, and defecated into his hand. As the feces began to freeze, he shaped it into the form of an implement. And when the blade started to take shape, he put a spray of saliva along the leading edge to sharpen it. That's when what they call the "shit knife" took form. He used it to butcher a dog. Skinned the dog with it. Improvised a sled with the dog's rib cage, and then, using the skin, he harnessed up an adjacent living dog. He put the shit knife in his belt and disappeared into the night.

Is that a true story?

True or not, it's a wonderful metaphor for the resilience of the Inuit people. Once during the migration of the belugas I was watching this Inuit guy fix his snowmobile. He cleaned the carburetor with this beautiful feather of an Arctic goose. Then he needed a new clutch plate and had to drive a hole through a piece of steel. He just put it between his two boots, got his 30-30 [rifle] out, and boom. And I thought, "Wow, these people can do anything."

Wait—the Inuit were on snowmobiles, not dogsleds? If everybody's going modern, what does it mean to preserve culture?

I don't believe in preserving culture. The real question is, what kind of world do we want to live in—a monochromatic world of monotony, or a polychromatic world of diversity? The idea is not to eliminate modernity, as if we've got the right to sequester people like some kind of specimen in a bubble. If I get my arm ripped off in a car accident, I don't want to be taken to a shaman; no one else does either.

But if the Inuit are living like us, how are they distinct?
The distinctions between cultures are not decorative—it's not feathers and bells or dancers or songs. Those are the symbols of culture. The essence of culture is a blanket of moral and ethical values that we place around the individual. It's culture that allows us to make sense out of sensation, to find order in a universe that may have none.

What about your own culture? Have you reflected on its meaning in your exploration of the world?
We don't think of ourselves as a culture in the West. We think that we somehow exist outside of time and culture. We're the real world moving inexorably forward: Get with it or lose the train. When the truth is, we're the anomaly. By a remarkable accident of geography, three of British Columbia's most important salmon rivers are all born within literally a stone's throw of each other in a rugged knot of mountains. The only other place I know like that is Tibet, where the Brahmaputra and Ganges are born in lakes on the lower flanks of Mount Kailash. That area is so revered that normally you are not even allowed to climb it. The idea of putting industrial infrastructure at the headwaters of those rivers would be anathema to Buddhist, Hindu, and Jain. Yet here we are about to embark upon coal-bed methane exploration and open anthracite coal mines right at the headwaters of our three greatest rivers in British Columbia. Not only are we prepared to do it, but we don't, even in the calculus of our economic planning, have a metric for the value of the land left alone. In other words, no company that wants to do something there has to compensate Canadians for destroying something so unique. But we think that this economic system of ours exists out of culture, out of time, and is the inexorable wave of history when, by definition, it is simply the product of a certain set of human beings: our lineage. I was raised in the forests of British Columbia to believe those forests existed to be cut. That has made me a human being very different from my friends amongst the Kwagiulth, who believed that those same forests were the abode of the crooked beak of heaven and the cannibal spirits that dwell at the north end of the world.

Given those conflicting perspectives, how can we ever make a connection, let alone straddle different worlds?
My friend Randy Borman was a young child born of American missionaries, Bub and Bobbie Borman. They were evangelizing the Kofán in lowland Ecuador in the late 1950s and '60s. The Kofán, meanwhile, were evangelizing Randy. He grew up a blond kid from the Midwest in the jungles of Ecuador in a totally isolated tribe. Kofán became his first language. He hunted with the elders and the other boys. He became thoroughly Kofán in every fiber of his being.

Then he tried to become an American, tried to attend university. He struggled for a semester and then went back to the jungle and married a Kofán woman. Before you know it, he's chief. Oil pipelines and colonization had swept into their homeland. It made perfect sense to them that their chief be a fellow whom they could trust, who could understand their ways but also understand the ways of the invader and could speak English and could speak Spanish and could negotiate in those silver towers in Quito.

Recently I was in Ecuador and I took ayahuasca with Randy and his father-in-law, a well-known shaman. As Randy said when he first showed microscopes to the Kofán, nothing in the dazzling array of organisms

+

displayed on the glass plate astonished them, because they already knew that multiple levels of reality existed. They had seen it in their visions.

A Tibetan monk turned to me once and said, “We don’t really believe in Tibet that you went to the moon, but you did. You may not believe we achieve enlightenment in one lifetime, but we do.”

+

FROM THE JULY 2008 ISSUE

Is the Universe Actually Made of Math?

Cosmologist Max Tegmark says mathematical formulas create reality.

By Adam Frank | Monday, June 16, 2008

RELATED TAGS: MATH, COSMOLOGY


photography by Erika Larsen

Cosmologists are not your run-of-the-mill thinkers, and Max Tegmark is not your run-of-the-mill cosmologist. Throughout his career, Tegmark has made important contributions to problems such as measuring dark matter in the cosmos and understanding how light from the early universe informs models of the Big Bang. But unlike most other physicists, who stay within the confines of the latest theories and measurements, the Swedish-born Tegmark has a night job. In a series of papers that have caught the attention of physicists and philosophers around the world, he explores not what the laws of nature say but why there are any laws at all.

According to Tegmark, "there is only mathematics; that is all that exists." In his theory, the mathematical universe hypothesis, he updates quantum physics and cosmology with the concept of many parallel universes inhabiting multiple levels of space and time. By posing his hypothesis at the crossroads of philosophy and physics, Tegmark is harking back to the ancient Greeks with the oldest of the old questions: What is real?

Tegmark has pursued this work despite some risk to his career. It took four tries before he could get an early version of the mathematical universe hypothesis published, and when the article finally appeared, an older colleague warned that his "crackpot ideas" could damage his reputation. But propelled by optimism and passion, he pushed on.

"I learned pretty early that if I focused exclusively on these big questions I'd end up working at McDonald's," Tegmark explains. "So I developed this Dr. Jekyll/Mr. Hyde strategy where officially, whenever I applied for jobs, I put forth my mainstream work. And then quietly, on the side, I pursued more philosophical interests." The strategy worked. Today a professor at the Massachusetts Institute of Technology, Tegmark travels among the world's top physicists. Backed by this well-earned credibility, his audacious ideas are sparking fascination and taking flight.

These days Tegmark is a busy man. With his wife, the Brazilian cosmologist Angelica de Oliveira-Costa, he balances science with the demands of raising two young boys. Our interviewer, theoretical astrophysicist Adam Frank of the University of Rochester in New York, finally caught up with Tegmark as he made his way home to Winchester, Massachusetts, from a conference at Stanford University. In a comic juxtaposition of the profound and the profane, they spoke about the nature of reality by cell phone for three hours as Tegmark jockeyed his way through an airport rental car return, security lines, and a long wait for a delayed flight. A riff on reality would brake to a halt so Tegmark could avoid being hit by a rental-agency van. Just as the conversation plunged into parallel universes, Tegmark would have to downshift the dialogue for the bewildered security guard checking his boarding pass. Tegmark's infectious excitement over the big issues, from physics and philosophy to kids and cosmology, made for one hell of an afternoon's ride.

Max, you have gained a reputation for thinking far outside the box even for a cosmologist. Have you always pondered deep questions of Life, the Universe, and Everything?
No. I was a very confused youth. I came to it all pretty late, and there was no one I talked about philosophy with as a teenager. I did have one friend in high school who did everything the opposite way from everyone else. If people were sending letters in rectangular envelopes, he would make triangular envelopes and send letters in those. I remember thinking, "That is cool. That is how I want to be."

Is that why you decided to go into physics?
Actually, my dad is a mathematician, and he was always very encouraging about math, but physics was my single most boring subject in high school. So I began as an undergrad in economics.

That was an interesting choice....When did physics show up on your radar screen again?
A friend gave me a book, *Surely You're Joking, Mr. Feynman!* by the physicist Richard Feynman. It was all about picking locks and picking up women. It had nothing to do with physics, but it struck me how between the lines it said loud and clear, "I love physics!" I couldn't understand how this could be the same boring stuff from high school. It really piqued my curiosity.

How so?
If you see some mediocre guy walking down the street arm in arm with Cameron Diaz, you say to yourself, "I'm missing something here." So I started reading Feynman's *Lectures on Physics* and I was like, whoa! Why haven't I realized this before?

So then you changed your major?
Umm, no. You don't pay for college in Sweden, so I was able to do this kind of scam where I enrolled in a different university to do physics without telling them I was already in college for economics.

You were in two colleges at the same time?
Yeah. You can see I was confused. It got complicated at times. I would have exams in both places on the same day, and I'd have to bike really fast between them.

Was it in college that you started to think about the bigger questions?
I was taking the one and only quantum physics class offered, and when I got to the chapter on measurement I felt sure that I was missing something.

You're talking about the way the observer appears to affect the measurement of what's being observed.
Right. There is this beautiful mathematical equation in quantum theory called the Schrödinger equation. It uses something called the wave function to describe the system you are studying—an atom, an electron, whatever—and all the possible ways that system can evolve. The usual perspective of quantum mechanics is that as soon as you measure something, the wave function literally collapses, going from a state that reflects all potential

outcomes to a state that reflects only one: the outcome you see at the moment the measurement is done. It seemed crazy to me. I didn't get why you were supposed to use the Schrödinger equation before you measured the atom, but then, while you're measuring it, the equation doesn't apply. So I got up my courage and knocked on the door of one of the most famous physicists in Sweden, a man on the Nobel committee, but he just blew me off. It wasn't until years later that I had this revelation that it wasn't me who didn't get it; it was him!

It is a beautiful moment in the education of a scientist when you realize that these guys in higher positions of power still don't have all of the answers. So you took your questions about the Schrödinger equation and the effect of measurement with you when you left for the United States and your Ph.D. at Berkeley?
That's where it all started for me. I had this friend, Bill Poirier, and we spent hours talking about crazy ideas in physics. He was ribbing me because I argued that any fundamental description of the universe should be simple. To annoy him, I said there could be a whole universe that is nothing more than a dodecahedron, a 12-sided figure the Greeks described 2,500 years ago. Of course, I was just fooling around, but later, when I thought more about it, I got excited about the idea that the universe is really nothing more than a mathematical object. That got me thinking that every mathematical object is, in a sense, its own universe.

Right from the start you tried to get this radical idea of yours published. Were you worried about whether it would affect your career?
I anticipated problems and did not submit until I had accepted a postdoctoral appointment at Princeton University. My first paper got rejected by three journals. Finally I got a good referee report from *Annals of Physics*, but the editor there rejected the paper as being too speculative.

Wait—that is not supposed to happen. If the referee likes a paper, it usually gets accepted.
That's what I thought. I was fortunate to be friends with John Wheeler, a Princeton theoretical physicist and one of my greatest physics heroes, who recently passed away. When I showed him the rejection letter, he said, "'Extremely speculative'? Bah!" Then he reminded me that some of the original papers on quantum mechanics were also considered extremely speculative. So I wrote an appeal to *Annals of Physics* and included Wheeler's comments. Finally the editors there published it.

Still, it wasn't your bread and butter. You did your Ph.D. and postdoc in cosmology, a totally different subject.
It's ironic that my cover for these more philosophical interests was cosmology, a field that has often been seen as flaky as well. But cosmology was gradually becoming more respectable because computer technology, space technology, and detector technology had combined to give us an avalanche of great information about the universe.

Let's talk about your effort to understand the measurement problem by positing parallel universes—or, as you call them in aggregate, the multiverse. Can you explain parallel universes?
There are four different levels of multiverse. Three of them have been proposed by other people, and I've added a fourth—the mathematical universe.

What is the multiverse's first level?
The level I multiverse is simply an infinite space. The space is infinite, but it is not infinitely old—it's only 14 billion years old, dating to our Big Bang. That's why we can't see all of space but only part of it—the part fron +

which light has had time to get here so far. Light hasn't had time to get here from everywhere. But if space goes on forever, then there must be other regions like ours—in fact, an infinite number of them. No matter how unlikely it is to have another planet just like Earth, we know that in an infinite universe it is bound to happen again.

You're saying that we must all have doppelgängers somewhere out there due to the mathematics of infinity.
That's pretty crazy, right? But I'm not even asking you to believe in anything weird yet. I'm not even asking you to believe in any kind of crazy new physics. All you need for a level I multiverse is an infinite universe—go far enough out and you will find another Earth with another version of yourself.

So we are just at level I. What's the next level of the multiverse?
Level II emerges if the fundamental equations of physics, the ones that govern the behavior of the universe after the Big Bang, have more than one solution. It's like water, which can be a solid, a liquid, or a gas. In string theory, there may be 10^{500} kinds or even infinitely many kinds of universes possible. Of course string theory might be wrong, but it's perfectly plausible that whatever you replace it with will also have many solutions.

Why should there be more than one kind of universe coming out of the Big Bang?
Inflationary cosmology, which is our best theory for what happened right after the Big Bang, says that a tiny chunk of space underwent a period of rapid expansion to become our universe. That became our level I multiverse. But other chunks could have inflated too, from other Big Bangs. These would be parallel universes with different kinds of physical laws, different solutions to those equations. This kind of parallel universe is very different from what happens in level I.

Why?
Well, in level I, students in different parallel universes might learn a different history from our own, but their physics would still be the same. Students in level II parallel universes learn different history and different physics. They might learn that there are 67 stable elements in the periodic table, not the 80 we have. Or they might learn there are four kinds of quarks rather than the six kinds we have in our world.

Do these level II universes inhabit different dimensions?
No, they share the same space, but we could never communicate with them because we are all being swept away from each other as space expands faster than light can travel.

OK, on to level III.
Level III comes from a radical solution to the measurement problem proposed by a physicist named Hugh Everett back in the 1950s. [Everett left physics after completing his Ph.D. at Princeton because of a lackluster response to his theories.] Everett said that every time a measurement is made, the universe splits off into parallel versions of itself. In one universe you see result A on the measuring device, but in another universe, a parallel version of you reads off result B. After the measurement, there are going to be two of you.

So there are parallel me's in level III as well.
Sure. You are made up of quantum particles, so if they can be in two places at once, so can you. It's a controversial idea, of course, and people love to argue about it, but this "many worlds" interpretation, as it is

called, keeps the integrity of the mathematics. In Everett's view, the wave function doesn't collapse, and the Schrödinger equation always holds.

The level I and level II multiverses all exist in the same spatial dimensions as our own. Is this true of level III?
No. The parallel universes of level III exist in an abstract mathematical structure called Hilbert space, which can have infinite spatial dimensions. Each universe is real, but each one exists in different dimensions of this Hilbert space. The parallel universes are like different pages in a book, existing independently, simultaneously, and right next to each other. In a way all these infinite level III universes exist right here, right now.

That brings us to the last level: the level IV multiverse intimately tied up with your mathematical universe, the "crackpot idea" you were once warned against. Perhaps we should start there.
I begin with something more basic. You can call it the external reality hypothesis, which is the assumption that there is a reality out there that is independent of us. I think most physicists would agree with this idea.

The question then becomes, what is the nature of this external reality?
If a reality exists independently of us, it must be free from the language that we use to describe it. There should be no human baggage.

I see where you're heading. Without these descriptors, we're left with only math.
The physicist Eugene Wigner wrote a famous essay in the 1960s called "The Unreasonable Effectiveness of Mathematics in the Natural Sciences." In that essay he asked why nature is so accurately described by mathematics. The question did not start with him. As far back as Pythagoras in the ancient Greek era, there was the idea that the universe was built on mathematics. In the 17th century Galileo eloquently wrote that nature is a "grand book" that is "written in the language of mathematics." Then, of course, there was the great Greek philosopher Plato, who said the objects of mathematics really exist.

How does your mathematical universe hypothesis fit in?
Well, Galileo and Wigner and lots of other scientists would argue that abstract mathematics "describes" reality. Plato would say that mathematics exists somewhere out there as an ideal reality. I am working in between. I have this sort of crazy-sounding idea that the reason why mathematics is so effective at describing reality is that it is reality. That is the mathematical universe hypothesis: Mathematical things actually exist, and they are actually physical reality.

OK, but what do you mean when you say the universe is mathematics? I don't feel like a bunch of equations. My breakfast seemed pretty solid. Most people will have a hard time accepting that their fundamental existence turns out to be the subject they hated in high school.
For most people, mathematics seems either like a sadistic form of punishment or a bag of tricks for manipulating numbers. But like physics, mathematics has evolved to ask broad questions.These days mathematicians think of their field as the study of "mathematical structures," sets of abstract entities and the relations between them. What has happened in physics is that over the years more complicated and sophisticated mathematical structures have proved to be invaluable.

Can you give a simple example of a mathematical structure?
The integers 1, 2, 3 are a mathematical structure if you include operations like addition, subtraction, and the like. Of course, the integers are pretty simple. The mathematical structure that must be our universe would be complex enough for creatures like us to exist. Some people think string theory is the ultimate theory of the universe, the so-called theory of everything. If that turns out to be true, then string theory will be a mathematical structure complex enough so that self-awareness can exist within it.

But self-awareness includes the feeling of being alive. That seems pretty hard to capture in mathematics.
To understand the concept, you have to distinguish two ways of viewing reality. The first is from the outside, like the overview of a physicist studying its mathematical structure. The second way is the inside view of an observer living in the structure. You can think of a frog living in the landscape as the inside view and a high-flying bird surveying the landscape as the outside view. These two perspectives are connected to each other through time.

In what way does time provide a bridge between the two perspectives?
Well, all mathematical structures are abstract, immutable entities. The integers and their relations to each other, all these things exist outside of time.

Do you mean that there is no such thing as time for these structures?
Yes, from the outside. But you can have time inside some of them. The integers are not a mathematical structure that includes time, but Einstein's beautiful theory of relativity certainly does have parts that correspond to time. Einstein's theory has a four-dimensional mathematical structure called space-time, in which there are three dimensions of space and one dimension of time.

So the mathematical structure that is the theory of relativity has a piece that explicitly describes time or, better yet, is time. But the integers don't have anything similar.
Yes, and the important thing to remember is that Einstein's theory taken as a whole represents the bird's perspective. In relativity all of time already exists. All events, including your entire life, already exist as the mathematical structure called space-time. In space-time, nothing happens or changes because it contains all time at once. From the frog's perspective it appears that time is flowing, but that is just an illusion. The frog looks out and sees the moon in space, orbiting around Earth. But from the bird's perspective, the moon's orbit is a static spiral in space-time.

The frog feels time pass, but from the bird's perspective it's all just one eternal, unalterable mathematical structure.
That is it. If the history of our universe were a movie, the mathematical structure would correspond not to a single frame but to the entire DVD. That explains how change can be an illusion.

Of course, quantum mechanics with its notorious uncertainty principle and its Schrödinger equation will have to be part of the theory of everything.
Right. Things are more complicated than just relativity. If Einstein's theory described all of physics, then all events would be predetermined. But thanks to quantum mechanics, it's more interesting.

But why do some equations describe our universe so perfectly and others not so much?
Stephen Hawking once asked it this way: “What is it that breathes fire into the equations and makes a universe for them to describe?” If I am right and the cosmos is just mathematics, then no fire-breathing is required. A mathematical structure doesn’t describe a universe, it is a universe. The existence of the level IV multiverse also answers another question that has bothered people for a long time. John Wheeler put it this way: Even if we found equations that describe our universe perfectly, then why these particular equations and not others? The answer is that the other equations govern other, parallel universes, and that our universe has these particular equations because they are just statistically likely, given the distribution of mathematical structures that can support observers like us.

These are pretty broad and sweeping ideas. Are they just philosophical musings, or is there something that can actually be tested?
Well, the hypothesis predicts a lot more to reality than we thought, since every mathematical structure is another universe. Just as our sun is not the center of the galaxy but just another star, so too our universe is just another mathematical structure in a cosmos full of mathematical structures. From that we can make all kinds of predictions.

So instead of exploring just our universe, you look to all possible mathematical structures in this much bigger cosmos.

If the mathematical universe hypothesis is true, then we aren’t asking which particular mathematical equations describe all of reality anymore. Instead we have to figure out how to separate the frog’s view of the universe—our observations—from the bird’s view. Once we distinguish them we can determine whether we have uncovered the true structure of our universe and figure out which corner of the mathematical cosmos is our home.
Max, this is pretty rarefied territory. On a personal level, how do you reconcile this pursuit of ultimate truth with your everyday life?
Sometimes it’s quite comical. I will be thinking about the ultimate nature of reality and then my wife says, “Hey, you forgot to take out the trash.” The big picture and the little picture just collide.

Your wife is a respected cosmologist herself. Do you ever talk about this over breakfast cereal with your kids?
She makes fun of me for my philosophical “bananas stuff,” but we try not to talk about it too much. We have our kids to raise.

Do your theories help with raising your kids, or does that also seem like two different worlds?
The overlap with the kids is great because they ask the same questions I do. I did a presentation about space for my son Alexander’s preschool when he was 4. I showed them videos of the moon landing and brought in a rocket. Then one little kid put up his hand and said: “I have a question. Does space end or go on forever?” I was like, “Yeah, that is exactly what I am thinking about now.”

FROM THE AUGUST 2008 ISSUE

The Lifesaving Work of the Man Behind "A Civil Action"

"Popular epidemiologist" Phil Brown comes to the aid of environmental contamination victims.

By Sheila Kaplan | Tuesday, July 29, 2008

RELATED TAGS: ENVIRONMENTAL POLICY, HEALTH POLICY, POLLUTION

photo by Christopher Churchill

As a child of parents who eked out a living in part by peeling potatoes and boiling borscht at resorts in New York State's Catskill Mountains, Phil Brown grew up with a natural empathy for people who didn't have much. He spent his childhood summers busing tables in the vacation area's lesser hotels. In winter his family would relocate to Florida, where his parents rented furnished apartments and worked in restaurants while Brown attended school.

Today Brown is a leading sociologist in the field of environmental health. After earning a doctorate in sociology at Brandeis University in 1979, he embarked on a career as an academic, soon joining the sociology department at Brown University. Although his focus was originally on mental health, environmental disasters impacting low-income communities, which often experienced far-reaching medical problems from exposure to toxins, would become his calling. In 1984 Brown's affinity for the working class took hold again when he arrived in the town of Woburn, Massachusetts, 12 miles north of Boston, along with a scientific team looking into an alarmingly high rate of leukemia in both children and adults: 19 cases in one decade, with only two survivors. The community's efforts to find the cause and its lawsuit against corporate giants W. R. Grace and Beatrice Foods were later detailed in Jonathan Harr's book *A Civil Action* and a movie of the same name.

The Woburn residents contended that chemicals from the factories had contaminated their water supply and caused the leukemia. Their grassroots efforts, led initially by a local mother whose son was diagnosed with acute lymphocytic leukemia, reminded Brown of the community effort at New York's Love Canal, whose residents, having assessed their own chemical contamination, challenged the government and the corporations they held responsible. It was an effort for which Brown coined the phrase "popular epidemiology."

A longtime professor of medical and environmental sociology at Brown University, Brown has championed the collaboration between impacted citizens and the scientific community. The effort made by the community of Woburn was chronicled in *No Safe Place*, the critically acclaimed book he coauthored with Edwin Mikkelsen.

We spoke with Phil Brown recently at his home in Cambridge, Massachusetts.

What is popular epidemiology?
It's where laypeople work together with scientists to look at the distribution and causes of illnesses—because otherwise a lot of those things would never even be looked at.

Was popular epidemiology considered fringe at first?
Certainly by other scientists. When the scientists involved at Woburn published their work, they got a lot of criticism because people felt that they were relying on anecdotal information. They were in particular criticized for using residents to do some of the interviewing. But the scientists couldn't have done it without them because they didn't have a budget.

So they recruited the Woburn residents and trained them to make sure they would avoid any bias. They were trying to find a whole lot of information about the residents' health, and they were also using water models to see how the water flowed—which houses got more water, which houses got less. Ultimately people who got more water were more likely to have leukemia.

What was it like to interview the residents?
These people were very angry. I mean, it was 20 years from the time that they first discovered the contamination until [the court case] finally ended. The main effect of the chemicals was childhood leukemia. And we interviewed some who had already lost their children. It was really, really hard. We would come out of there wiped out. I had never really had that experience before, scientifically talking to people who had lost their kids. It was a very hard thing.

So we did these interviews, and Mikkelsen and I wrote *No Safe Place*. It was pretty well received, in The *New York Times Book Review*, in *Nature* and *Science*. It's still cited today as a key work in the field.

The *New York Times* said that your book was for people "who are mad as hell and aren't going to take it anymore." What impact did it have?

In terms of contributing to my field, shaping a new way of looking at environmental activism and environmental health more generally, I felt like I was building some new arena of work that I wanted to spread.

You shifted away from the field of mental health after your work in Woburn.

Once I wrote the book, I was hooked. I completely changed my focus. I stopped teaching most of my mental health classes at Brown and began working on a mix of medical and environmental sociology, environmental justice, contested illnesses—that is, illnesses whose environmental causes are contested.

How do you define your work?
It's multidisciplinary. You have to understand the sociology of a place, the political science, the toxicology, the epidemiology. You have to have the facilities to do the lab research, to take the samples, to run the analytical studies on them. So all the things that I'm doing and my colleagues are doing are multidisciplinary. That's really what makes it very exciting. And there are always community organizations and individuals who are very involved with this.

In your role as a sociologist, isn't there a conflict in helping the people whom you're studying?

I understand not everybody is going to be comfortable with it. Not all sociologists have to do that. And I know that for someone who is a junior faculty member without tenure it may seem risky.

Do you see yourself as both scientist and advocate?
Yes, it has to be seen as a back-and-forth, because there are things that we know that the community doesn't know. They know that there's contamination. They don't know how to measure it. But we can teach them with very high-tech scientific equipment how to do that. Then they can say, "All right, here are the samples. You send them to the lab." The lab sends it back to us as the scientists. We can analyze it, then tell the people, "We found this many parts per million" or "This is 12 times higher than we've ever measured" or "It's 100 times higher than it's ever been seen. What do you think? What are you going to do about it?"

So they're coming up with ideas, and they're also pointing out new ways to interpret it. That's what all of my colleagues who do this kind of work find—that they learn so much scientifically.

Who are the naysayers?
The chemical companies and some parts of state and federal public health agencies. They don't want to be flooded with requests to do these studies. They are getting requests by the hundreds from people who are concerned about cancer clusters and, increasingly, people concerned about other diseases—autisms, Lou Gehrig's disease, clusters of lupus. The more you look, the more you are finding this.

How do corporations respond to popular epidemiology?
They argue that scientists are being led by the nose by citizens and that when you have ordinary people formulating research questions and hypothesizing or being involved in the study, it makes it illegitimate, it takes away the good science.

What's to stop "popular epidemiologists" from skewing their research to support the findings they want?

They are not collecting data alone but doing it in partnership with scientists. And the kind of scientists involved in such collaborations have a high degree of ethics. Further, they are highly visible as allies of the activists and residents, and that visibility makes them an easy target; hence, they won't fake data or let laypeople do so. They realize that failure to be honest and transparent would jeopardize the individual case, the broader social movement, and their own careers.

Who are the advocates?
Increasingly more groups around the country are doing studies of their own. Sometimes they are doing health studies and trying to correlate health problems with exposures…trying to find what they think is a plausible outcome. At Hanford [a decommissioned nuclear production facility in Washington State] they did something called dose reconstruction, where they looked at releases of radiation and the wind patterns and how the wind might have traveled. That's hard to do for citizen groups.

Another example is the Drift Catcher Project. Using air sampling buckets, people are finding wide drifts of pesticides beyond the spraying fields. They are doing that in California and in other states. It's become a very big thing. These citizen alliances are very, very powerful.

Tell me about Tiverton, Rhode Island. It's close to your home and Brown University.
The town was putting new sewer lines in, and as they were digging they found a lot of blue soil, which immediately looked really weird and dangerous. They called in the Department of Environmental Management (DEM), and they learned it was very heavily contaminated with arsenic, with a lot of polycyclic aromatic hydrocarbons (PAHs), and with other things contained in waste from a manufactured gas plant.

It was such severe contamination that the town government said, "You are not allowed to dig here. You can't garden. You can't add on to your house. You can't fix a basement. You can't do anything. You can't put a fence post in the ground."

How large an area is it?
It's about 120 homes. It's a neighborhood in the north part of Tiverton, the Bay Street neighborhood, sloping down to the bay.

They were really in bad shape, because if you couldn't dig and it was known that you had this problem, well, there was no way that you'd ever be able to sell your house. And they couldn't even get a home equity loan. That was one of the first things that struck me. These are really very hard-working, working-class people, and this is like the only equity they have in their lives.

So they came up to me at this meeting and they said, "We heard that you're from Brown and maybe you could help us." I put them onto a colleague of mine…and [he and his students] worked with them and helped to get together some of the history of their problems and their efforts to get the gas company to remediate, and to get the state to clean it up.

You're in the middle of a project now studying how people in communities educate themselves and organize on environmental issues. How did that get started?
It came out of a project we did on Cape Cod. We asked people if they understood the way we provided information—graphs that we did for them, which gave individual data on pollutants in their bodies and their homes.

This is a very new area, and people don't often get these results back. At best, people get one result back, like lead. We were testing for 89 different chemicals and providing 20 or 30 results per person. So we asked if they understood them, and we asked questions like: Does it make them think of ways to change their exposure, if they can? Does it make them think about what the causes might have been?

They were generally very surprised to find a lot of contaminants in their homes. Sometimes they were trying to figure out where they came from. They were concerned about the uncertainty. They wanted to know, could this have caused so-and-so's illness? We can't tell them that these things had certain effects.

Then you took this methodology to Richmond, California?
We wanted to find a way to make our type of analysis useful in other places. Richmond, we knew, had a long history of concern about refineries and the port. It's a very highly burdened area, mainly low income and largely people of color. This is not talked about a lot yet, but for black women there is a more virulent form of breast cancer. So we, and groups like Breast Cancer Action and the Breast Cancer Fund, were starting to think about environmental causes of breast cancer.

We spent a lot of time working with them ?on how this study should be designed, how we would all benefit from it in different ways, and building up a partnership and talking to each other a lot, meeting a lot.

They organized and went door-to-door. We trained them to do it. They put air monitors in place, and we did the analysis when the data came back and helped them figure out the best way to present it.

Was there opposition from the other side?
There's always local opposition. "You're going to hurt our tax base," they say. "You're going to give [us] a bad name. People are not going to want to move here."

What's your response when that happens?
I wrote in *No Safe Place* that one of our biggest opponents [in Woburn] was the town engineer. And then he dies from contamination. So you can't be safe from this stuff. And you can't even live in a different part of town or a different part of the country because this stuff is traveling. The more we learn about emerging contaminants, the more we know that you don't have to produce PCBs someplace to have them show up in your blood. They're showing up in the Arctic. They're getting there by ocean currents and air currents. And by, you know, biomagnifications in the food chain [the accumulation of substances in increasingly high concentrations as larger organisms feed on smaller ones].

So that's just going to keep happening. People are going to see, hopefully, that you can't just live in a pure, pristine place and you can't just buy green products and organic food. There's still enough stuff around that's going to hurt you.

Do you always win?
No. There were some things that we lost in Providence, Rhode Island, recently—schools being constructed on very contaminated land. Despite opposition from the community, from Rhode Island Legal Services, and from the state itself, the city still went ahead and built these schools.

What was the land contaminated with?
In the first instance it was an old Providence city landfill. In the second case it was the Gorham silver plants. Gorham was the biggest silver manufacturer in the world, and they had, I think, 12,000 workers. You can imagine how big it was. So there was a lot of old electroplating and metalwork in Rhode Island in general. And this was one of the biggest. It's very contaminated.

What is the next step for the community groups, and how will you try to help them?
The first two schools that were built were an elementary and a middle school next to each other, the Springfield Street Schools. The residents filed a lawsuit, and the outcome of the lawsuit was that the judge said you have to monitor the place and you also have to have DEM set up a statewide panel which will have citizens and experts in government to develop a new environmental-justice approach to brownfields [polluted and abandoned industrial sites].

So I'm actually on that panel, and there are a bunch of residents on that panel too. And while not everybody is happy with how it's going, nevertheless that's one positive outcome of this.

What has popular epidemiology changed?
It's changed citizens' belief that they didn't matter to a belief that they could matter…It has benefited many people suffering from toxic releases or from plumes of contaminants under their soil or from dumps, or proposed power plants or other plants, such as the concrete plants just defeated in Cranston, Rhode Island. It's emboldened a lot of people to say, "We may not be the most educated, the most influential, but we can stand up and do this together."

FROM THE NOVEMBER 2008 ISSUE

The "Monkey Whisperer" Learns the Secrets of Primate Economics

Laurie Santos penetrates the world of monkeys... and finds they're more like humans than we think.

By Linda Marsa | Monday, October 13, 2008

RELATED TAGS: PRIMATES, ANIMAL INTELLIGENCE, HUMAN EVOLUTION, MEMORY, EMOTIONS, & DECISIONS, LEARNING

photo by Jeffery Salter

It's feeding time at the Myakka City Lemur Reserve, a leafy 90 acres about 25 miles east of Sarasota, Florida. On this steamy morning in early March, baskets containing pellets of monkey chow, fruit, and other treats drop from the trees onto a clearing. Three ferretlike brown lemurs, the pint-size alpha dogs of the preserve, make a beeline for the food. They elbow aside their less aggressive—and slightly affronted—brethren: the red-ruffed lemurs, sporting stiff Elizabethan collars of fur, and the hypervigilant ring-tailed lemurs, whose facial markings and luxurious striped tails give the impression of svelte raccoons.

Yale University psychologist Laurie Santos squats on the ground surrounded by half a dozen of these curious primates. They regard her quizzically while she takes pictures of them with a digital camera. The photos aren't keepsakes of her field trip but will be used to help her comprehend the social structure of lemurs, specifically whether they have an affinity for forming social cliques.

Lemurs, from the island of Madagascar off the coast of Africa, evolved in isolation for some 30 million years. Despite this long separation from the rest of the primates, they now have something in common with a group of rhesus macaques in Puerto Rico and capuchin monkeys living at Yale: They all contribute to Santos's wide-ranging study of our primate relatives, offering an unparalleled glimpse into our evolutionary past. Monkeys, it turns out, have many of the same survival skills that we do, from a predilection for forming groups to a knack for taking risks and deceiving adversaries.

Santos's studies show that monkeys also possess many of the quirks and foibles once considered uniquely human. Like us, they intuit what others are thinking by reading social cues, a skill that may be millions of years old, hardwired into the primate brain. They make the same errors in economic reasoning that we do, suggesting our sometimes irrational attitude toward money might once have conferred an evolutionary edge. Through a series of groundbreaking experiments, Santos has seen in her primates a humanlike propensity for hoarding, larceny, and competitiveness. By exploring the inner lives of primates, she has offered persuasive evidence that monkeys are capable of sophisticated insight, complex reasoning, and calculated action.

Although the 33-year-old New Bedford, Massachusetts, native grew up surrounded by cats and dogs—her mother is a pet rescuer —Santos originally aimed for a career in law. The switch to studying animal behavior was, she says, “utterly serendipitous.” Shut out of a prelaw seminar in her freshman year at Harvard, she took a psychology class that ultimately led her to the study of nonhuman primates. She was captivated. Now an associate professor at Yale and head of the university’s Comparative Cognition Laboratory, Santos explains to DISCOVER how she learned to think like a monkey—and, in the process, came to understand more about how humans think too.

You first observed monkeys with your mentor at Harvard, the evolutionary psychologist Marc Hauser. What intrigued you?

Initially it was just the opportunity to go to his field site on this island near Puerto Rico. But when I saw the monkeys, I got hooked. Watching them, you can’t help but see that they have the same kinds of issues that we do. They play. You can see their social striving. You can see their battles, their caring. They want to make friends and mate and be on top. They care about their kids, and they want their friends to do well.

One day I was alone on the beach and I picked out a nice spot to eat. A monkey came and sat beside me, and he had his monkey chow and was eating. We sat there together and I wondered what this monkey was thinking. Did he think the spot was beautiful? And how would I know that he did? That got me thinking about how they’re a lot like us, but on the other hand so different. They’re navigating these complicated motor situations, jumping from tree to tree, dealing with the stresses of new environments, and foraging. They do all of this minus language, minus the kind of social and cultural learning we humans have, yet they live, they mate, and they do some extremely complicated things, particularly in the social domain. How they achieve these same ends minus computers, BlackBerrys, or tape recorders is fascinating.

Your research with rhesus macaques in Puerto Rico suggests that they are capable of discerning human intentions. How did you realize that they were studying you even as you were studying them?

The monkeys were good at deception. Nowadays when out in the field we eat lunch inside a cage that we bring along, in part because the monkeys have gotten very good at stealing our lunch. And it’s not just the food we eat but the fruit we use as stimuli in our testing sessions. Many days we went home early because the monkeys ate all the fruit. We would be doing number experiments where one plus one is supposed to equal two. But with only one lemon left, they can’t add one plus one and we can’t test their addition skills. In order for the monkeys to have taken the lemons when we didn’t notice, they must have paid attention to what we could see and what we couldn’t see. They’d have to wait for the moment we were no longer looking, and step in and take the lemons away.

So they were watching you intently?

Not just watching us but specifically paying attention to the cues that were related to whether or not we could see, whether our eyes were pointed toward the lemons. You’d turn to write in your notebook and you’d look up and there was a monkey running up the hill.

That led us to develop a series of experiments where we directly asked whether or not the monkeys were good at using cues, such as where eyes are pointed. The real question is this: Are the monkeys just good at reading our behavior? "Oh, she's turned away now." Or are they thinking about our perceptions, mainly "She can't see now." And this is still a question of much controversy in the field.

Do you think that, in a very rudimentary way, these monkeys were able to read your mind?
To the extent that they're reading behavioral cues that are correlated with mental states—things they can't see—yes, they are mind readers. But do they know that you have a mind in the first place? Do they understand that we have thoughts?

One of the most basic mental states that we think about in others involves perceptions—what you can see or hear—and that builds up to what you know or don't know. The ability to discern these states in others was probably enormously powerful back in the evolutionary day, when we grew up as social primates who lived and died on the basis of how well we were able to predict others' social actions: Are you going to be a friend to me? Are you going to back me up later?


photo by Jeffery Salter

How do you go about exploring monkey awareness of human perception?
The simplest study uses two experimenters standing on either side of a platform holding two portions of food. One of the experimenters can see the food and the other can't because they are facing in opposite directions. They get into position near a monkey who is all by himself, and the monkey gets one trial to steal the food. And the question is, who does he steal the food from? Consistently the monkeys steal the food from the guy who's facing away. Even without training, they realize that when eyes are pointed at them, it's probably not a good idea to do it. But as soon as eyes are turned away, all bets are off.

Other studies suggest that monkeys pick up on what we can hear. We have a single experimenter who has two boxes. One is covered in jingle bells, so when it moves it makes a lot of noise. The other one looks the same because it's covered in jingle bells, but we've taken the balls out of all the bells, so the monkey can hear that when the experimenter puts food in the box it's not making any sound. So when the experimenter freezes and looks away, the question is, which box does the monkey steal from? What we find is that they sneak over and take food out of the quiet box and avoid stealing things from the box they know is noisy.

You've also begun researching economic behavior in capuchin monkeys. How did this study come about?
Some of the capuchins in our colony at Yale came from a lab where the males had already learned how to tra

tokens for food. It was funny when the monkeys first arrived because one of the caretakers said we had "genius" monkeys. "They hand their orange peels back to us so we don't have to clean the cages," he said. And then I realized it was because they had been trained in token-trading behavior.

So they were using every available scrap to get more food?
Yes, they were pretty crafty—trying to negotiate even before we set up market experiments of our own.

How did you establish a barter system among the capuchins?
We set the monkeys up with different human traders who offered things at different rates. When I started at Yale, I was lucky enough to have a colleague, Keith Chen, who is an economist and had already been collaborating with Marc Hauser at Harvard. We got together for drinks one night and started talking about ways to set up these experiments. We started with a series of studies examining whether capuchins pay attention to the "price" of food and whether they switch their purchasing behavior when items go "on sale"—if they buy more of the foods when they're on sale to maximize the amount of food they're getting. The easiest way to do these studies is to find two objects the monkeys like about equally, like apples and Jell-O cubes. The monkeys have their little wallet of 12 tokens, and they can spend them any way they like. There are two "salesmen," one selling apples and the other selling Jell-O. What we found is the monkeys spend half their budget on apples and half on Jell-O. The next day, one experimenter has the regular-size apples but the guy selling Jell-O is offering two cubes for the price of one. And lo and behold, just like a human would, they buy more Jell-O. We showed that the monkeys' market sense is very similar to our own.

But you also began to focus on the monkeys' mistakes.
I was interested in the errors that people make and looking for ways to study those errors in the monkeys.

Why focus on human error?
Humans do a lot of systematically dumb things. The way we categorize things is biased and leads to stereotypes. Our judgments are biased when we deal with finances, but why? We've hypothesized that maybe some of these errors were built in from the beginning, which is why they're so hard to get rid of. And if that's the case, then these kinds of biases might be shared with other primates, which leads to the question of whether they are really biases in the first place. Maybe they're smart for something that is just wrong for our modern environment.

What kinds of errors are we talking about?
One source of error is an innate aversion to loss. Basically it's the same experimental setup: There are two salespeople. One of them looks like he's offering one piece of apple, but when the monkey pays him, that experimenter delivers a bonus—an extra piece of apple. So the monkeys get two, which they think is pretty good. The second salesman looks like he's going to give the monkey three pieces of apple because he's holding three pieces. But when the monkeys pay him, he takes one of these pieces away, so the monkeys see a loss of one piece of apple.

The important thing is that, on average, the monkeys get two pieces of apple from both experimenters. So in practice they shouldn't care and should trade randomly, but that's not what we see. The monkeys prefer to trade with the experimenter who's giving them the bonuses and avoid the experimenter who's giving them the losses.

What does this tell you about irrational economic behavior?
Economists assume that our decisions are based on what's going to give us the most wealth or happiness. But the monkeys violate the assumption that all they care about is the amount of food they get. They also seem to care about how the amount of what they get differs from what they expected.

Have the monkeys surprised you in any other ways?
We did a similar study in a risky context, where both experimenters start out offering three pieces of something. The first experimenter appears to offer three items but each time ultimately gives the monkey two, so the monkey gets a loss, but it's a safe, consistent loss. The second experimenter starts out offering three but introduces more risk: Sometimes the monkey gets all three, but sometimes it gets only one. We find that the monkeys prefer to go with the second experimenter. They prefer to risk losing more because there is also a chance they will have no loss at all. That is just what humans do.

It sounds like the falling housing market. People stay in because it could ultimately go up, but meanwhile, the whole thing might crash and burn. Where is the evolutionary advantage in this?
My guess is that the strategy worked in the kinds of unstable, variable environments in which we evolved. Say you're foraging for nuts and you're in a really bad way—if you don't get five you're going to die. If you haven't found five nuts yet, you need to take a lot of risk to get them because the alternative is really bad. As seen in the housing market, people take more risk when facing loss than they do when dealing with gain.

There was a famous experiment done by the psychologists Daniel Kahneman and Amos Tversky back in the 1980s involving a hypothetical Asian disease that is expected to kill 600 people. There are options for fighting the outbreak. In one scenario, 400 people will die for certain. In another scenario, there's a one-third chance that no one will die and a two-thirds chance that everyone, all 600, will die. What do you pick? When framed that way, people will choose the riskier scenario because they want the slim possibility that there's not going to be any loss. The housing market is another case in point. You'll risk an even bigger loss just on the chance that you might not have any loss at all.

You've also studied another kind of bias: the tendency to devalue what we don't have, a "sour grapes" attitude.
Human experiments suggest that when forced to decide between two things we like equally, we end up devaluing the object we chose against. The Aesop's fable of the sour grapes is a prime example of wanting something but when you find out you can't have it, you decide you never liked it anyway.

The way we tested this in monkeys was to offer different-colored M&Ms, which the monkeys liked equally. We gave the monkeys a choice between, say, red and blue, and they picked blue. Then the question was, what happened to the M&Ms that the monkeys didn't choose? Did they irrationally dislike those more than they had before? To get at that, we then gave them a choice between red—the one they chose against—and a novel color, like green.

The prediction was that the monkeys would pick more of the green. And that's just what they did, which suggests they've irrationally devalued red M&Ms because they'd had to make an arbitrary choice about those a few seconds earlier.

And how might this bias provide an evolutionary advantage?
Often we make a decision and then change our beliefs to fit the decision. When things don't match up, we may try to resolve the dissonance through rationalization. It might be the case that your cognitive system strives for consistency in a way that leads to correct inferences about the world later on.

You've said that monkeys make the same reasoning errors humans do. Do you think monkeys can reason?
I do. They obviously can't verbally reason things out, but their choices are extremely similar to the ones humans make. So in that sense, I think they have to be reasoning.

Why do you study lemurs when other primates are far more like us, both genetically and behaviorally?
Lemurs are important to study because they're so distantly related to humans. If we see the same cognition in lemurs that we also see in macaques, capuchins, and chimpanzees, it allows us to learn more about how old that kind of cognition is. The other thing is that the lemurs developed in such a different environment on the island of Madagascar. So if we see the same kind of abilities in them, those abilities are probably widespread across primates.

Sort of like behavioral carbon dating?
Yes. That is the logic we use. If we find the same capacity in lemur species and in our capuchin monkeys at Yale and in the macaques we've been working with in Puerto Rico—if all these branches at the top of the tree have this capacity—then it probably didn't evolve separately, and it is probably something that we all shared back in the day.

For instance, we found lemurs are as good as a six-month-old human baby at adding and subtracting objects. We showed the lemurs one lemon entering a box, and then a screen came up so they couldn't see what was in the box anymore. Then we showed them another lemon being placed in the box. Then we would remove the screen and reveal either the correct outcome of two objects in the box or incorrect outcomes of three objects or one object.

Our measure of whether the lemurs expected this was based on how long they looked at it. The assumption was that if it was what they expected, they'd be bored and turn away. But if it was something that surprised them or that they found unexpected, they'd look longer. And that's just what they did. All the lemur species looked longer at events where we showed them the incorrect outcome.

You also discovered that lemurs can use tools, even though they don't use them in the wild.

It turned out the lemurs were very good at picking up on the features that were relevant for the tool's function. While they lack the capacity to set it up from scratch—to create a tool—they still understand how to use it.
What does that finding suggest for human evolution?

One of the working hypotheses is that we have a set of simple physical and social capacities that help us function and make sense of how things work. And that provides the scaffolding for learning that can take place when you're in an environment that has lots of tools. These are basic building blocks for all the stuff we learn later.

This set of capacities seems to be shared broadly across the primate order and seems to come online in humans early in their development. Whether you grow up as a hunter-gatherer in Africa or a modern-day human in Sarasota or a baby lemur in the forest, you seem to have these simple capacities.

Will we eventually discover that nonhuman primates have a complicated inner life?
How much they feel is still a big open question. Do they feel loved? Do they feel emotional pain? We still don't have good measures. But in terms of how they think, we use the same measures that we use in humans, and our studies suggest primates are reasoning about things they can't see and interpreting mental states. Just a few years ago, we didn't think primates could do this. Animals' mental lives are richer than we used to think.

Fifty years from now, are we going to look back on the way we handled other primates and think of it as barbaric?
The hope is that seeing more of ourselves in them will help us treat them more humanely and work to conserve them and their habitats in future generations. Our experiments suggest that these primates can understand our intentions. Can they morally reason about what we do? Can they understand someone's intent to hurt them? When we get the full package of how they pay attention to the world, it might end up informing how we treat them.

FROM THE JANUARY 2009 ISSUE

Why Did Western Drs. Promote Tobacco While the Nazis Fought Cancer?

Robert Proctor looks at the way knowledge advances—and sometimes takes great leaps backwards.

By Thomas Broening, Michael Abrams | Thursday, January 08, 2009

RELATED TAGS: CANCER

Pop quizzes are frequent for students in Robert Proctor's history of science classes. "How old is the earth?" "How many millions in a billion?" "Are you convinced that humans share a common ancestry with apes?" Proctor's passion is figuring out not only what his students know, but also what they don't know. His drive is to explore aspects of science that most don't see.

A professor of the history of science at Stanford University, Proctor has taught courses as varied as "The Changing Concept of Race," "Tobacco and Health in World History," and "Human Origins: Evidence, Ideology, and Controversy." His ever-roving eye tends to focus on bad science made during good times, good science made in bad times, and the mass of ignorance lodged in our collective minds as a result of both.

Proctor is living what he calls "the ultimate dabbler's fantasy," taking on subjects that appeal to his questioning spirit. But the motivation behind that dabbling is often principled outrage and a drive to right wrongs. Some of those wrongs are big ones—he has been the scourge of the tobacco industry, testifying against it in many cases and writing books and articles about what those in the industry knew, when they knew it, and how they campaigned to hide certain facts. Other wrongs are seemingly small: Proctor notes that the agates he collects and polishes, although unique and rare, are considered cheap, while diamonds, plentiful and homogeneous, somehow have great value.

Last May saw the release of Proctor's latest book, *Agnotology: The Making & Unmaking of Ignorance*, coedited with Londa Schiebinger. DISCOVER caught up with him at his Stanford office.

Just what is agnotology?

It's the study of the politics of ignorance. I'm looking at how ignorance is actively created through things like military secrecy in science or through deliberate policies like the tobacco industry's effort to manufacture doubt through their "doubt is our product" strategy [spelled out in a 1969 tobacco company memo [pdf]]. So it's not that science inherently always grows. It can actually be destroyed in certain ways, or ignorance can actually be created.

How common is the active creation of ignorance?

It's pretty common. I mean, in terms of sowing doubt, certainly global warming is a famous one. You know, the global warming denialists who for years have managed to say, "Well, the case is not proven. We need more research." And what's interesting is that a lot of the people working on that were also the people working for Big Tobacco.

Really?

Yeah. The techniques of manufacturing doubt were created largely within the tobacco industry, and then they were franchised out to other industries. I have a chapter in my book *Cancer Wars* called "Doubt Is Our Product," which is about the hundreds and hundreds of different industries that use these techniques of sowing doubt in order to minimize hazard, as do various trade associations. One of their goals is the idea of sowing doubt or questioning statistics. And they're very powerful. You know the old saying: For every Ph.D. there's an equal and opposite Ph.D.

You have a unique take on the relationship between ideology and science.

Bad ideologies can produce good science, and good ideologies can produce bad science. In my book *The Nazi War on Cancer*, I showed that a horrific ideology can produce world-class science, and in my human origins work I showed that liberal antiracism can produce bad science.

One of the things I teach in my class is that the history of science is the history of confusion, and there are many, many confusions. In a lot of my work I look at how even crazy prejudices can sometimes create good science. For instance, we all think the Nazis were crazy, but in fact, you know, they did some amazing science—not just in spite of their ideology, but actually because of their ideology. And that's the same with all strong ideologies. The Piltdown hoax [the 1912 discovery of a supposed skull of early man, which 40 years later was determined to be a human cranium and ape jaw fraudulently joined together] was actually perceived [as a hoax] fairly early on by creationists because they refused to believe that this could have been a real skull.

What are other examples of good science coming from bad ideologies?

We tend to forget that the first manned space flight was produced at the height of the Soviet empire. I think the example of Mayan archaeoastronomy is an interesting one. There you have very competent elites who are involved in sort of blending calendrical astronomy with human sacrifice. That gets pretty hairy.

How did you develop this line of interest?

Well, I have a lot of curiosity about the world. I'm very interested in combining science with politics and ethics. And I like to do what I call activist history of science—a history of science that is relevant to present-day policy and present-day suffering and also to historical suffering. So I like to use history to inform the present, but I also like to use the present to inform history.

It seems you have endless curiosity.
I'm amazed by people who don't ask questions constantly. I was raised to think that the good life is asking questions and then always realizing that there are infinitely many more questions and that basically what we know is an infinitesimal part of what we might know. I'm interested in human suffering. I'm interested in the big, unanswered questions—in the massive infinity of ignorance that we swim in.

Have you continued your focus on tobacco?
I recently collaborated on an exhibit of the most outrageous tobacco ads called "Not a Cough in a Carload." It's centered on medical-themed tobacco ads: that tobacco's good for your T-zone, that it calms your nerves. Scientific tests prove that brand A is better than B, or, you know, 20,000 physicians recommend Camels, and so forth. The use of athletes and models, and the artwork is just beautiful.

How did this kind of marketing come about?
It was pioneered by the tobacco industry. They set out to have a massive public relations campaign to defend tobacco at all costs against science. They wanted science that was good PR. I think it's mainly a post–World War II phenomenon, although there are a couple of exceptions if you go back earlier for specific industries. In the 1920s, lead was almost banned from both paint and gasoline, and the lead industry set out to have a campaign that softened the critiques. And then in the 1930s, you get Big Tobacco manufacturing consumer drive and convincing people this is a cool, natural thing to do, so it's part of the history of marketing. It's the applying of marketing techniques to science, which is rather diabolical in a lot of ways.

You've been very involved in tobacco litigation. What is the history of that industry's response to challenges?

The tobacco industry started responding particularly in the 1950s with propaganda. That's when they started their doubt campaign—the manufacturing of doubt, the manufacturing of ignorance. It was really rather new, certainly on the scale at which they pursued it. It was a new way of using science as an instrument of deception. And that's become important recently. Franchised down into the global warming issue are the same techniques. Demanding ever-greater precision, invoking doubt, questioning the physical methods. Raising alternate possibilities. The whole realm of smoke screens and distractions.

How do you maintain the perspective essential to your kind of research?
Well, I have three emotional principles in all my work. One is wonder, another is sympathy, and the third is critique. These are virtues of different disciplines that are generally not combined. Wonder we think of as a traditional scientific discipline or motive. It's great to wonder at the grandeur and glory of the universe, the childlike wonder, the Stephen Jay Gould wonder, the Einsteinian wonder.

But there's also the traditional historical virtue of sympathy, which is to realize that the world we live in really is kind of a moment in time when we have the entire history of the universe behind us that we can explore as well. And when it comes to human interpretation, it's important to see the past the way the people saw it. So I've written two books on Nazi medicine, and the goal there was not just to condemn them, but to see how in the world they came up with those ideas and those movements and how they justified them to themselves. So we see them as full humans and not just scarecrows, so we can actually understand the depth of the depravity or whatever. But at least we see it honestly, and that's a traditional historical virtue.

The third principle is critique, which is to realize that we're humans first. If we're cosmologists or historians, we're at least humans first and then cosmologists and historians. We need to critique and show that there's a lot of garbage out there, and we don't want to be apologists for some horrific status quo where people are dying by the millions. And so we don't just want to see things through other people's eyes and we don't want to just wonder at the glory of nature. We want to realize that there's horrific suffering in the world and that we, as humans and as scholars, have a duty to do something about it.

Should other scientists be driven by the same motives?

I think they're good principles, certainly. We need to see the big picture. Scientists are often involved in work that's just a small fraction of the picture. There are going to be specific motives for the research we do. Geology is centered on exploration for new fuels and things like that. But anytime we decide to fund one type of research rather than another, that's a kind of political decision. It's a social decision. It's a collective decision about what we want to view as important.

You work in such widely different fields. Why didn't you choose a specialty?

Something is lost when people specialize. I like to see things like an amateur. The word amateur is literally "lover," it's from amore. Professionalism is often the death of intellectual inquiry. So I think there's a kind of virtue of systematic amateurism that really needs to be rekindled. If you don't love and hate and play and joke with your objects of study, then you're really not treating them properly. I tell my students if you're not angry and excited and enthralled by your topic, you should choose a different one.

How difficult is it to always be sorting out truth from lies—and to spend so much time thinking about ignorance?

I'm not a skeptic; I'm a pragmatist. I think we have to live in the world and can't be skeptical of everything. Trust is a fundamental part of being human. You have to evaluate the source, but you can't be hypercritical or you'd drive yourself crazy. I believe in the common sense of most people. There's a great deal of common sense in the world. There's also a lot of common ignorance. It's nearly boundless.

FROM THE FEBRUARY 2009 ISSUE

What Makes You Uniquely "You"?

Nobel laureate Gerald Edelman says your brain is one-of-a-kind in the history of the universe.

By Susan Kruglinski | Friday, January 16, 2009

RELATED TAGS: LEARNING, SENSES, ANIMAL INTELLIGENCE, MENTAL HEALTH, MACHINE-BRAIN CONNECTIONS, EVOLUTION OF INTELLIGENCE

Some of the most profound questions in science are also the least tangible. What does it mean to be sentient? What is the self? When issues become imponderable, many researchers demur, but neuroscientist Gerald Edelman dives right in.

A physician and cell biologist who won a 1972 Nobel Prize for his work describing the structure of antibodies, Edelman is now obsessed with the enigma of human consciousness—except that he does not see it as an enigma. In Edelman's grand theory of the mind, consciousness is a biological phenomenon and the brain develops through a process similar to natural selection. Neurons proliferate and form connections in infancy; then experience weeds out the useless from the useful, molding the adult brain in sync with its environment.

Edelman first put this model on paper in the Zurich airport in 1977 as he was killing time waiting for a flight. Since then he has written eight books on the subject, the most recent being *Second Nature: Brain Science and Human Knowledge*. He is chairman of neurobiology at the Scripps Research Institute in San Diego and the founder and director of the Neurosciences Institute, a research center in La Jolla, California, dedicated to unconventional "high risk, high payoff" science.

In his conversation with DISCOVER contributing editor Susan Kruglinski, Edelman delves deep into this untamed territory, exploring the evolution of consciousness, the narrative power of memory, and his goal of building a humanlike artificial mind.

This year marks the 150th anniversary of *The Origin of Species*, and many people are talking about modern interpretations of Charles Darwin's ideas. You have one of your own, which you call *Neural Darwinism*. What is it?

Many cognitive psychologists see the brain as a computer. But every single brain is absolutely individual, both in its development and in the way it encounters the world. Your brain develops depending on your individual history. What has gone on in your own brain and its consciousness over your lifetime is not repeatable, ever—not with identical twins, not even with conjoined twins. Each brain is exposed to different circumstances. It's very likely that your brain is unique in the history of the universe. *Neural Darwinism* looks at this enormous variation in the brain at every level, from biochemistry to anatomy to behavior.

Before talking about how this relates to consciousness, I'd like to know how you define consciousness. It's hard to get scientists even to agree on what it is.
William James, the great psychologist and philosopher, said consciousness has the following properties: It is a process, and it involves awareness. It's what you lose when you fall into a deep, dreamless slumber and what you regain when you wake up. It is continuous and changing. Finally, consciousness is modulated or modified by attention, so it's not exhaustive. Some people argue about qualia, which is a term referring to the qualitative feel of consciousness. What is it like to be a bat? Or what is it like to be you or me? That's the problem that people have argued about endlessly, because they say, "How can it be that you can get that process—the feeling of being yourself experiencing the world—from a set of squishy neurons?"

What is the evolutionary advantage of consciousness?
The evolutionary advantage is quite clear. Consciousness allows you the capacity to plan. Let's take a lioness ready to attack an antelope. She crouches down. She sees the prey. She's forming an image of the size of the prey and its speed, and of course she's planning a jump. Now suppose I have two animals: One, like our lioness, has that thing we call consciousness; the other only gets the signals. It's just about dusk, and all of a sudden the wind shifts and there's a whooshing sound of the sort a tiger might make when moving through the grass, and the conscious animal runs like hell but the other one doesn't. Well, guess why? Because the animal that's conscious has integrated the image of a tiger. The ability to consider alternative images in an explicit way is definitely evolutionarily advantageous.

I'm always surprised when neuroscientists question whether an animal like a lion or a dog is conscious.
There is every indirect indication that a dog is conscious—its anatomy and its nervous system organization are very similar to ours. It sleeps and its eyelids flutter during REM sleep. It acts as if it's conscious, right? But there are two states of consciousness, and the one I call primary consciousness is what animals have. It's the experience of a unitary scene in a period of seconds, at most, which I call the remembered present. If you have primary consciousness right now, your butt is feeling the seat, you're hearing my voice, you're smelling the air. Yet there's no consciousness of consciousness, nor any narrative history of the past or projected future plans.

How does this primary consciousness contrast with the self-consciousness that seems to define people?
Humans are conscious of being conscious, and our memories, strung together into past and future narratives, use semantics and syntax, a true language. We are the only species with true language, and we have this higher-order consciousness in its greatest form. If you kick a dog, the next time he sees you he may bite you or run away, but he doesn't sit around in the interim plotting to remove your appendage, does he? He can have long-term memory, and he can remember you and run away, but in the interim he's not figuring out, "How do I get Kruglinski?" because he does not have the tokens of language that would allow him narrative possibility. He does not have consciousness of consciousness like you.

How did these various levels of consciousness evolve?
About 250 million years ago, when therapsid reptiles gave rise to birds and mammals, a neuronal structure probably evolved in some animals that allowed for interaction between those parts of the nervous system involved in carrying out perceptual categorization and those carrying out memory. At that point an animal could construct a set of discriminations: qualia. It could create a scene in its own mind and make connections with past scenes. At that point primary consciousness sets in. But that animal has no ability to narrate. It cannot

construct a tale using long-term memory, even though long-term memory affects its behavior. Then, much later in hominid evolution, another event occurred: Other neural circuits connected conceptual systems, resulting in true language and higher-order consciousness. We were freed from the remembered present of primary consciousness and could invent all kinds of images, fantasies, and narrative streams.

So if you take away parts of perception, that doesn't necessarily take away the conceptual aspects of consciousness.

I'll tell you exactly—primitively, but exactly. If I remove parts of your cortex, like the visual cortex, you are blind, but you're still conscious. If I take out parts of the auditory cortex, you're deaf but still conscious.

But consciousness still resides in the brain. Isn't there a limit to how much we can lose and still lay claim to qualia—to consciousness—in the human sense?

The cortex is responsible for a good degree of the contents of consciousness, and if I take out an awful lot of cortex, there gets to be a point where it's debatable as to whether you're conscious or not.

For example, there are some people who claim that babies born without much cortex—a condition called hydran-encephaly—are still conscious because they have their midbrain. It doesn't seem very likely. There's a special interaction between the cortex and the thalamus, this walnut-size relay system that maps all senses except smell into the cortex. If certain parts of the thalamocortical system are destroyed, you are in a chronic vegetative state; you don't have consciousness. That does not mean consciousness is in the thalamus, though.

If you touch a hot stove, you pull your finger away, and then you become conscious of pain, right? So the problem is this: No one is saying that consciousness is what causes you to instantly pull your finger away. That's a set of reflexes. But consciousness sure gives you a lesson, doesn't it? You're not going to go near a stove again. As William James pointed out, consciousness is a process, not a thing.

Can consciousness be artificially created?

Someday scientists will make a conscious artifact. There are certain requirements. For example, it might have to report back through some kind of language, allowing scientists to test it in various ways. They would not tell it what they are testing, and they would continually change the test. If the artifact corresponds to every changed test, then scientists could be pretty secure in the notion that it is conscious.

At what level would such an artifact be conscious? Do you think we could make something that has consciousness equivalent to that of a mouse, for example?

I would not try to emulate a living species because—here's the paradoxical part—the thing will actually be nonliving.

Yes, but what does it mean to be alive?
Living is—how shall I say?—the process of copying DNA, self-replication under natural selection. If we ever create a conscious artifact, it won't be living. That might horrify some people. How can you have consciousness in something that isn't alive? There are people who are dualists, who think that to be conscious is to have some kind of special immaterial agency that is outside of science. The soul, floating free—all of that.

There might be people who say, "If you make it conscious, you just increase the amount of suffering in this world." They think that consciousness is what differentiates you or allows you to have a specific set of beliefs and values. You have to remind yourself that the body and brain of this artifact will not be a human being. It will have a unique body and brain, and it will be quite different from us.

If you could combine a conscious artifact with a synthetic biological system, could you then create an artificial consciousness that is also alive?
Who knows? It seems reasonably feasible. In the future, once neuroscientists learn much more about consciousness and its mechanism, why not imitate it? It would be a transition in the intellectual history of the human race.

Do you believe a conscious artifact would have the value of a living thing?
Well, I would hope it would be treated that way. Even if it isn't a living thing, it's conscious. If I actually had a conscious artifact, even though it was not living, I'd feel bad about unplugging it. But that's a personal response.

By proposing the possibility of artificial consciousness, are you comparing the human brain to a computer?
No. The world is unpredictable, and thus it is not an unambiguous algorithm on which computing is based. Your brain has to be creative about how it integrates the signals coming into it. And computers don't do that. The human brain is capable of symbolic reference, not just syntax. Not just the ordering of things as you have in a computer, but also the meaning of things, if you will.

There's a neurologist at the University of Milan in Italy named Edoardo Bisiach who's an expert on a neuropsychological disorder known as anosognosia. A patient with anosognosia often has had a stroke in the right side, in the parietal cortex. That patient will have what we call hemineglect. He or she cannot pay attention to the left side of the world and is unaware of that fact. Shaves on one side. Draws half a house, not the whole house, et cetera. Bisiach had one patient who had this. The patient was intelligent. He was verbal. And Bisiach said to him, "Here are two cubes. I'll put one in your left hand and one in my left hand. You do what I do." And he went through a motion.

And the patient said, "OK, doc. I did it."

Bisiach said, "No, you didn't."

He said, "Sure I did."

So Bisiach brought the patient's left hand into his right visual

+

field and said, “Whose hand is this?”

And the patient said, “Yours.”

Bisiach said, “I can’t have three hands.”

And the patient very calmly said, “Doc, it stands to reason, if you’ve got three arms, you have to have three hands.” That case is evidence that the brain is not a machine for logic but in fact a construction that does pattern recognition. And it does it by filling in, in ambiguous situations.

How are you pursuing the creation of conscious artifacts in your work at the Neurosciences Institute?
We construct what we call brain-based devices, or BBDs, which will be increasingly useful in understanding how the brain works and modeling the brain. They may also be the beginning of the design of truly intelligent machines.

What exactly is a brain-based device?
It looks like maybe a robot, R2-D2 almost. But it isn’t a robot, because it’s not run by an artificial intelligence [AI] program of logic. It’s run by an artificial brain modeled on the vertebrate or mammalian brain. Where it differs from a real brain, aside from being simulated in a computer, is in the number of neurons. Compared with, let’s say, 30 billion neurons and a million billion connections in the human cortex alone, the most complex brain-based devices presently have less than a million neurons and maybe up to 10 million or so synapses, the space across which nerve impulses pass from one neuron to another.

What is interesting about BBDs is that they are embedded in and sample the real world. They have something that is equivalent to an eye: a camera. We give them microphones for the equivalent of ears. We have something that matches conductance for taste. These devices send inputs into the brain as if they were your tongue, your eyes, your ears. Our BBD called Darwin 7 can actually undergo conditioning. It can learn to pick up and “taste” blocks, which have patterns that can be identified as good-tasting or bad-tasting. It will stay away from the bad-tasting blocks, which have images of blobs instead of stripes on them —rather than pick them up and taste them. It learns to do that all on its own.

Why is this kind of machine better than a robot controlled by traditional artificial intelligence software?
An artificial intelligence program is algorithmic: You write a series of instructions that are based on conditionals, and you anticipate what the problems might be. AI robot soccer players make mistakes because you can’t possibly anticipate every possible scenario on a field. Instead of writing algorithms, we have our BBDs play sample games and learn, just the way you train your dog to do tricks.

At the invitation of the Defense Advanced Research Projects Agency, we incorporated a brain of the kind that we were just talking about into a Segway transporter. And we played a match of soccer against Carnegie Mellon University, which worked with an AI-based Segway. We won five games out of five. That’s because our device learned to pick up a ball and kick it back to a human colleague. It learned the colors of its teammates. It did not just execute algorithms.

It's hard to comprehend what you are doing. What is the equivalent of a neuron in your brain-based device?
A biological neuron has a complex shape with a set of diverging branches, called dendrites, coming from one part of the center of the cell, and a very long single process called an axon. When you stimulate a neuron, ions like sodium and potassium and chloride flow back and forth, causing what's called an action potential to travel down the neuron, through the axon, to a synapse. At the synapse, the neuron releases neurotransmitters that flow into another, postsynaptic neuron, which then fires too. In a BBD, we use a computer to simulate these properties, emulating everything that a real neuron does in a series of descriptions from a computer. We have a set of simple equations that describe neuron firing so well that even an expert can't tell the difference between our simulation spikes and the real thing.

All these simulations and equations sound a lot like the artificial intelligence ideas that haven't been very successful so far. How does your concept for a conscious artifact differ?
The brain can be simulated on a computer, but when you interface a BBD with the real world, it has the same old problem: The input is ambiguous and complex. What is the best way for the BBD to respond? Neural Darwinism explains how to solve the problem. On our computers we can trace all of the simulated neuronal connections during anything the BBD does. Every 200 milliseconds after the behavior, we ask: What was firing? What was connected? Using mathematical techniques we can actually see the whole thing converge to an output. Of course we are not working with a real brain, but it's a hint as to what we might need to do to understand real brains.

When are we going to see the first conscious artifact emerge from your laboratory?
Eugene Izhikevitch [a mathematician at the Neurosciences Institute] and I have made a model with a million simulated neurons and almost half a billion synapses, all connected through neuronal anatomy equivalent to that of a cat brain. What we find, to our delight, is that it has intrinsic activity. Up until now our BBDs had activity only when they confronted the world, when they saw input signals. In between signals, they went dark. But this damn thing now fires on its own continually. The second thing is, it has beta waves and gamma waves just like the regular cortex—what you would see if you did an electroencephalogram. Third of all, it has a rest state. That is, when you don't stimulate it, the whole population of neurons stray back and forth, as has been described by scientists in human beings who aren't thinking of anything.

In other words, our device has some lovely properties that are necessary to the idea of a conscious artifact. It has that property of indwelling activity. So the brain is already speaking to itself. That's a very important concept for consciousness.

FROM THE MARCH 2009 ISSUE

DNA Agrees With All the Other Science: Darwin Was Right

Molecular biologist Sean Carroll shows how evolution happens, one snippet of DNA at a time

By Pamela Weintraub | Thursday, February 19, 2009

RELATED TAGS: EVOLUTION, GENETICS, SEX & REPRODUCTION

Photo by Saverio Truglia

When Sean Carroll was a graduate student at Tufts School of Medicine in Boston, he found himself seduced by spectacular new studies of the humble fruit fly. That work, which eventually won a Nobel Prize for its principals, showed that modifying a single gene during a fly's embryonic development could transform the insect's body plan: Instead of becoming an antenna, a body extension could develop into a leg. Carroll continued to study these genes and, some years later, found that they were not restricted to fruit flies; they turned out to be part of a master tool kit that sculpts the body structures of all animals, ranging from humans to nematode worms.

The discovery of this small set of universal body-building genes gave Carroll and others a fresh way to explore the inner workings of evolution. By observing how the genes changed during the course of embryonic development, scientists could track the emergence of a novel physical trait, the first step toward the creation of a new species. For the first time, researchers had direct access to the machinery of evolution and could actually watch it in the act. A new science, known as evolutionary developmental biology, or evo devo, was born.

One of the great triumphs of modern evolutionary science, evo devo addresses many of the key questions that were unanswerable when Charles Darwin published On the *Origin of Species* in 1859, and Carroll has become a leader in this nascent field. Now a professor of molecular biology and genetics at the University of Wisconsin, he continues to decode the genes that control life's physical forms and to explore how mutations in those genes drive evolutionary change. These days, Carroll also devotes increasing energy to telling the public about his field's remarkable discoveries through a series of books—*Endless Forms Most Beautiful*, *The Making of the Fittest*, and the brand-new *Remarkable Creatures*. He spoke with DISCOVER senior editor Pamela Weintraub about what his work has taught him about Darwin, the nature of evolution, and how life really works.

It has been 150 years since Charles Darwin proposed his theory of evolution in *On the Origin of Species*, yet in some ways the concept of evolution seems more controversial than ever today. Why do you think that is?

It is a cultural issue, not a scientific one. On the science side our confidence grows yearly because we see independent lines of evidence converge. What we've learned from the fossil record is confirmed by the DNA record and confirmed again by embryology. But people have been raised to disbelieve evolution and to hold other ideas more precious than this knowledge. At the same time, we routinely rely on DNA to convict and exonerate criminals. We rely on DNA science for things like paternity. We rely on DNA science in the clinic to weigh our disease risks or maybe even to look at prognoses for things like cancer. DNA science surrounds us, but in this one realm we seem unwilling to accept its facts. Juries are willing to put people to death based upon the variations in DNA, but they're not willing to understand the mechanism that creates that variation and shapes what makes humans different from other things. It's a blindness. I think this is a phase that we'll eventually get through. Other countries have come to peace with DNA. I don't know how many decades or centuries it's going to take us.

In your new book, *Remarkable Creatures*, you relate how Darwin arrived at his theory of evolution. Can you connect the dots?

As a college student Darwin collected beetles. He was looking for more opportunities to collect when there came this opportunity to be a naturalist on the British ship the HMS Beagle. It was seductive. He could go to faraway places—visit the tropics, places of incredible richness of life relative to cold, damp, gray England. It was difficult to persuade his father to allow him to go—he was just 22—but he got the chance. Two stops in this five-year journey were pivotal. The first came early in the voyage when he arrived on the coast of Argentina and unearthed fossils of many species, including some unknown to science—for instance, fossils of giant, extinct sloths that had been enormous compared with the living sloths he saw in the South American forests. So it planted the seed in his mind that life had changed.

Then Darwin got to the Galápagos Islands. He went from island to island collecting birds—mockingbirds and then finches—and realized that even when the birds appeared to be similar, on each island they were slightly different. After he left the Galápagos, on his way home to England, the lightbulb went on. He realized that if these birds lived on such similar islands but were slightly different from one another, there could be just one explanation: They had started out as a single species, but over time and with separation they had drifted apart and changed.

This insight was widely regarded as heresy, but why?

The prevailing idea was called special creation: that every species was created by a supernatural power and put in place on the earth for a specified role in a specified time by a completely mysterious process. It wasn't open to natural science. Instead, Darwin said no, species are changeable, and the introduction of new species is a completely natural process that follows natural laws just the way physics does. A fundamental aspect of human existence has been to ask how we got here. Evolution is the big answer to that big question. Obviously there are alternative answers that have prevailed for a very long time, but evolution has replaced a supernatural explanation of human origins with a naturalistic one.

Is that why Darwin waited more than 20 years to publish his theory of evolution?

Beneath diverse exteriors, all animals share a set of body-building genes. If I had five minutes with Darwin, I would start right there. It would blow his mind.

Darwin was a pretty insecure 22-year-old when he boarded the ship. As these thoughts started to occur to him by the time he was about 27, he was just getting his feet under himself back in England. He realized what these thoughts meant, but he was just being accepted into scientific circles, just getting a lot of attaboys. Why risk that? This was not a time to challenge the establishment. You have to look at Darwin the human being to understand why he would not spill the beans.

What piqued your own interest in evolution?
As a kid, I was fascinated by zebras and giraffes and leopards. I kept snakes, and I loved their color patterns. As I got older I asked deeper questions—mainly, how are pattern and form generated? One of the most spectacular pageants on earth involves a complex creature developing from a single fertilized egg. Anyone who's a parent is still amazed that it works. When I was a graduate student, we could watch this happen, but we didn't understand the mechanics. What was going on inside that would put limbs in the right place, put eyes in the right place, carve the circulatory system and the backbone? It was an irresistible mystery, made even more irresistible with the realization that what makes a snake different from a lizard, what makes a zebra different from a giraffe, are changes within that developmental process. Understanding development was a passport to two fundamental questions: How does a complex creature form from an egg, and how have different types of creatures evolved?

These seem like two very disparate ideas: the embryonic development of a single specimen and the evolution of a whole species. How did they get connected?
At first paleontologists were studying evolution on vast timescales through fossils. Then geneticists came on the scene, and they were studying small-scale differences within species based on mutations in genes. What has been called the modern synthesis of the two fields emerged in the 1940s with the idea that the sorts of genetic differences you could observe in populations, right out your window, when compounded and extrapolated over vast periods of time, could account for the large-scale changes we see in the fossil record. So the modern synthesis was a harmonization of those two scales.


Photo by Saverio Truglia

But the modern synthesis did not explain evolution in full. It was still just a theory. Where was the empirical evidence? Darwin's theory of descent was a black box. You could not see exactly what kinds of changes were taking place to account for the differences in forms. But the study of embryonic development has allowed us to peer into the machinery of making these creatures. We can study their DNA text and their developing embryos and ask, where do the differences arise? That gave us the empirical data for the theory. You can't necessarily see the change happening in the adult, but you can see that if you change that nucleic acid base right there in that gene, at that particular point in embryonic development, that animal is darker. If you change those three bases over there, that limb is longer. This is the fundamental basis of evolution: changes in DNA. By experimenting with it and visualizing it all the way up the ladder of differences, we now understand that the modern synthesis is correct.

+

You've said evolution is like compounding interest. How so?
Just like a good money market account, evolution works through incremental change. If variants within a species provide an advantage, no matter how slight, then that form, that capacity, will be favored. If evolving spots on wings makes you more attractive to mates or more evasive to predators, those patterns will dominate. Those varieties will have more offspring. Added up over centuries, millennia, and longer periods of time, natural selection—the competition that takes place in nature between variant forms—is powerful enough to forge all the changes that we've seen on the face of the earth.

It is hard for most people to wrap their brains around such vast stretches of time.
A century ago, Teddy Roosevelt was president and cars were barely in use. That seems like an unimaginable amount of time ago, but biologically and geologically speaking, it was a split second. A million years is just a fraction of the time that upright hominids have had to evolve. It takes time for sea levels to rise, for rivers to cut their course. As temperatures change, as rain forests grow up or deserts emerge, the creatures that live in these regions are adapting and changing too.

You call the combination of evolution and embryonic development evo devo. What is that, exactly?
It is just shorthand for "evolutionary developmental biology," a mini-syllabic description of this field that's concerned with the evolution of development. It's related probably to Devo, the new-wave band of the early 1980s—those were the guys who played with dog dishes on their heads. Before then you could describe evolution as change over time, but we did not have any grip on that process until the 1980s.

And that's when you entered the scene?
Right. I was in graduate school doing research in immunology at Tufts University in Boston. I would just hop on the subway and go to seminars at three or four different schools. It's stimulation, right? It's hard to know how all the dots got connected, but I kept hearing that things were not well understood in evolution and things were not well understood in development, and I started thinking: How can I get at the meat? I was looking around for insights when I came across the very thin literature on the genes that sculpt fruit fly bodies, including the study of spectacular mutants. In these mutants, or Frankenflies, a single gene could put legs on the head in place of antennae. Other single-gene mutations gave the flies an extra set of wings or removed its eyes or wings completely. The fact that single-gene mutations could have such dramatic effects raised the question: What were these genes, and what were they meant to do? The quest was to figure out how these genes sculpted the fruit fly body form.

You saw the fruit fly as a window into evolution and development. How did you make the connection?
It was not an obvious call, because the expectation was that fruit flies didn't have anything to do with the development of furry creatures. But in 1983 I found a laboratory where I could do the work, with Matt Scott at the University of Colorado at Boulder. Just as we were getting started, it became clear from our research and others' that these body-building genes were not restricted to fruit flies; they were shared throughout the animal kingdom. It was a real jolt. All of a sudden we could do deep experiments at the most fundamental level to understand how form actually evolved.

So scientists were seeing the same master genes at work in many different species?
Yes. One shocking discovery was the relationship between our eyes and bug eyes. You wouldn't think they ha

anything in common, right? Bug eyes, with 800 facets, work by different optical principles than human eyes. For almost a century and a half, biologists thought that they had evolved independently, from scratch, and that eyes had been invented many times in the animal kingdom by completely different means—different recipes in different groups of animals. We have now discovered that these eyes are formed by what is recognizable as the same gene, even though those animals have been evolving separately for 500 million years. When we took the mouse version of this gene—the same gene we find in the human—and put it in the fly and tweaked it, we induced fly eye tissue.

Our team showed that the same common gene is critical to building limbs in humans and fruit flies. It turns out that this gene is critical to building virtually everything that sticks out of the body: antennae, legs, horns, whatever. These kinds of experiments shattered our preconceptions and forced people to think differently. Beneath these extremely diverse exteriors was a deeply shared common genetic tool kit. If I had five minutes with Charles Darwin, I'd start right there. It would blow his mind.

Clearly we have entered the age of experimental Darwinism. What are the experiments like, specifically?

We look at lots of species to figure out the ancestral form of a particular molecule. We can reconstruct that ancestral molecule and then retrace the steps that must have taken place to forge the new forms and functions we see today. If you think that the difference between two species involves changes in certain genes, you can swap those genes between the species. We're doing those experiments trait by trait. There's a powerful set of experiments that people have done on vision. Lots of animals differ in the parts of the color spectrum that they see best because of how they are tuned to their environments —whether they live in the deep sea or in caves, whether they mostly go out in the day or at night, or whether they're trying to pick up ultraviolet patterns on flowers or on prey. Sight is really important in helping animals live, and since animals live in lots of different habitats, vision has evolved a lot.

Experiments that look at these changes are very doable in the lab. You can swap genes and change the retinal proteins that detect light. Then you can make very clear predictions about what certain changes mean and verify those things experimentally. For example, mice have been given an extra color vision gene in the lab, and it has been shown that the protein manufactured by that gene expands the scope of their vision by enhancing their ability to see longer-wavelength light without any other changes in the brain.

Can we apply these discoveries to the human realm?

We now know that the human genome and the chimp genome differ by only about 1 percent. Yet our bodies and brains are so different. How can we be so different from other primates if our genes are so much the same? How did we get the dexterity in our hands? How do we walk upright? How are we able to hold this conversation? How did we get big brains? Once you identify the meaningful functional changes that have taken place between us and chimps, you realize that pretty big differences in anatomy and behavior can result from a small degree of genetic divergence. Evo devo has given us the tools to explore this mystery: The same genes are being regulated and then used in a different way. Something is happening a little earlier or in another place or is staying on a little bit longer. These are the time and space dimensions of development. It's like choreography. You've got the same dancers, but the ballet is different based on different cues.

In your book *Endless Forms Most Beautiful*, you refer to the Cambrian explosion, a time when a vast number of new life-forms appeared at nearly the same time. Evolutionary skeptics often

point to this kind of abrupt shift—doesn't such rapid change contradict your description of a single master tool kit and slow evolution over long stretches of time?
Prior to about 543 million years ago, you saw things like jellyfish and spongelike creatures, but you didn't see bilateral creatures: worms and trilobites and things like this. Then in the Cambrian explosion, large and complex animal forms erupted. These forms in the Cambrian represent a lot of the major divisions of the animal kingdom we see today. The Cambrian explosion looks abrupt in the fossil record, but the surprising message from evo devo is that all the genes for building big, complex animal bodies long predated the appearance of those bodies. Most of what was needed to create this incredible complexity already existed. The genes were expressed prior to the Cambrian in those more modest, soft-bodied creatures, but they had fewer jobs to do. Complexity evolved by expanding the uses of these genes rather than inventing lots more of them.

It makes you wonder what kind of potential is just waiting to burst out today.
Dinosaurs were the dominant vertebrates right up until the end of the Cretaceous. Mammals existed, but they were smaller, carving lifestyles out of the dinosaurs' way. Take out the dinosaurs and in 10 or 15 million years mammals had evolved into all sorts of large forms and dominated terrestrial ecosystems. When genetic potential met ecological opportunity, you got elephants and bison and giraffes. Think about ecology as corking the bottle; take the cork out and things explode.

You mention in your book *The Making of the Fittest* that every species contains fossil genes.
These are remnants that are no longer used, and the integrity of the genetic text starts to erode. One of my favorite stories concerns the ice fish of Bouvet Island. These creatures live in the cold waters of the Antarctic. They are the only vertebrates without red blood cells to carry oxygen to nourish their tissues. If you look at the genes for hemoglobin, the oxygen-carrying proteins in red blood, one of those genes is completely gone and another is a broken remnant, rotting away. From this we understand that the ancestors of these fish had red blood, but these guys have left that red-blooded lifestyle behind.

When genetic potential met ecological opportunity, you got elephants and bison and giraffes. Ecology is like corking the bottle; take the cork out and things explode.

The explanation is ecological. The ice fish are living in this extremely cold water, and it may well be that red blood cells are really hard to pump around capillaries in such cold water. Instead, the fish have larger gills and pretty much a scaleless skin. So they're just getting their oxygen passively from the surrounding ocean water. They've abandoned a way of life that has nourished vertebrates for some 500 million years. As for us, humans have junked about 800 genes in the course of our evolution from mammalian and earlier ancestors going back millions of years. Who knows, those lost genes might be useful to us 1,000 years from now, but there's no way to preserve them. I guess we could always try to engineer some things back in.

By contrast, you've said that some genes are immortal.
These genes date back to the early origin of life on the planet, and they're so essential that their text has been preserved for more than 3 billion years. They're involved in very fundamental ways with the decoding of the genetic machinery shared among all organisms. Without these genes you couldn't express your genetic information and produce the proteins you need to live.

+

You've presented an avalanche of irrefutable evidence, yet opponents of evolution seem to refute it all. How do you respond?

You can hear me almost chuckling, because it's not reasonable, it's not rational, and as the years click by, it's ever more preposterous, but people still stick to their guns.

Is there anything we can do to help persuade the skeptical public to accept the evolutionary way of looking at life?
Seriously, teach evolution as a core theme in science from the early grades. The universe changes, the earth changes, and life changes with the evolving earth.

Where do you see evolutionary biology going next?
Today we're in a second golden age. We're not collecting the menagerie of critters that Darwin did or hauling them back to a museum. Instead, we're collecting the genetic recipes of creatures across the planet and trying to figure out how they came to be. We're looking right into the text of evolution, and even into the text of extinct creatures like woolly mammoths and Neanderthals, and we're asking what made them similar to or different from elephants or from us.

A third golden age will come when we understand life beyond earth. How many times has life evolved, and how many origins have there been? Has life moved from planet to planet? Is the chemistry of extraterrestrial life different from that of life on earth? This will be difficult work, but we have to look ahead. Finding life elsewhere in the universe would bring a scientific revolution as big as any we've ever had.

Click here to see DISCOVER's special package on Darwin in honor of his 200th birthday and the 150th anniversary of The Origin of Species.

FROM THE APRIL 2009 ISSUE

The Man Who Found Quarks and Made Sense of the Universe

Murray Gell-Mann had a smash success with particles, notorious dustups with Feynman, and a missed opportunity with Einstein.

By Susan Kruglinski | Tuesday, March 17, 2009

RELATED TAGS: SUBATOMIC PARTICLES

Photo by Jamey Stillings

It is no accident that the quark—the building block of protons and neutrons and, by extension, of you and everything around you—has such a strange and charming name. The physicist who discovered it, Murray Gell-Mann, loves words as much as he loves physics. He is known to correct a stranger's pronunciation of his or her own last name (which doesn't always go over well) and is more than happy to give names to objects or ideas that do not have one yet. Thus came the word quark for his most famous discovery. It sounds like "kwork" and got its spelling from a whimsical poem in James Joyce's *Finnegans Wake*. This highly scientific term is clever and jokey and gruff all at once, much like the man who coined it.

Gell-Mann's obsession with words dates to his youth, when his fascination with linguistics, natural history, and archaeology helped him understand the diversity of the world. The native New Yorker skipped three grades in elementary school and entered college early. After zipping through Yale and MIT, Gell-Mann was just 21 when he began his postdoc work at the Institute for Advanced Study in Princeton, New Jersey, back when Albert Einstein was still strolling the campus. Gell-Mann later worked with Enrico Fermi at the University of Chicago, and he debated passionately with renowned physicist Richard Feynman during his many years at Caltech.

It was at Caltech that Gell-Mann helped to lay the foundations for our understanding of the components that make up matter. He drafted a blueprint of subatomic physics that he called the Eightfold Way. At the time, physicists understood that atoms are constructed from protons and neutrons, but they had also found many other mysterious particles. The Eightfold Way made sense of this baffling menagerie, finding within it places for particles never even imagined. The work was so important that it netted Gell-Mann a Nobel Prize in 1969.

In 1984 Gell-Mann pursued his dream of working in other fields by cofounding the Santa Fe Institute, a think tank where scientists are encouraged to cross disciplines. Located high on a hill in the New Mexico desert, surrounded by cottonwood trees and outcroppings of rose quartz, the institute is a place where an ornithologist can trade data over lunch with a political scientist while excitedly scrawling statistical equations on a window with a Sharpie for lack of paper and pen. With its geometric design, brightly colored walls, abundant hiking trails in the vicinity, and generous supply of candy in the kitchen, the Santa Fe Institute seems a bit like a playground for scientists.

DISCOVER contributing editor Susan Kruglinski recently sat with Gell-Mann among the oversize leather couches in the institute's cozy library to talk about what it is like to have lived the history of modern physics.

You are best known as the person who discovered the quark, one of the fundamental particles that make up the universe, yet for years many of your colleagues weren't convinced that quarks really existed. Why not?
You can't see them directly. They have some unusual properties, and that's why it was difficult for people to believe in them at the beginning. And lots of people didn't. Lots of people thought I was crazy. Quarks are permanently trapped inside other particles like neutrons and protons. You can't bring them out individually to study them. So they're a little peculiar in that respect.

How should a nonphysicist visualize quarks? As tiny spheres trapped inside atoms?
Well, in classical physics you could think of a quark as a point. In quantum mechanics a quark is not exactly a point; it's quite a flexible object. Sometimes it behaves like a point, but it can be smeared out a little. Sometimes it behaves like a wave.

When people picture particles smashing together in a particle collider, what should they be imagining? It's not like billiard balls colliding, is it?
It depends on the circumstances. At very high energies, two particles that smash together do not bounce off each other but create a vast number of particles. You would have all sorts of little chips flying off in all directions—that would be a little more like it.

So it would be like smashing an apple and an orange together and getting bananas?
No, no, no. Little bits of all kinds of things. Getting a whole bunch of little chips of apple and orange, but also chips of banana and antibanana, grapes...

How many types of elementary particles are there?
We have a thing called the standard model, which is based on about 60 particles, but there may be many more. These are just the ones that have a low energy, so we can detect them.

The 1960s and 1970s could be considered a heyday of particle physics, when many subatomic particles—and not just elementary ones, it turns out—were being discovered. Could you talk a little bit about the events leading up to your discovery of the quark?
That was very dramatic for me. I had been working for years on the properties of particles that participated in the strong interaction. This is the interaction responsible for holding the nucleus of the atom together. The family of strongly interacting particles includes the neutrons and protons; those are the most familiar ones. But now tens, dozens, hundreds of other particles were being discovered in experiments in which protons collided with each other in particle accelerators. There were lots and lots of energy states in which we saw relatives—cousins—of the neutrons and protons.

These particles are similar to protons and neutrons but don't normally exist in nature?
They are produced in a particle collision in an accelerator, and they decay after a short time. After a tiny fraction of a second, they fall apart into other things. One particle that I predicted, the omega-minus, can decay into a neutral pion and xi-minus, and then the pion decays into photons, and the xi-minus decays into a negative pion and a lambda. And then the lambda decays into a negative pion and a proton. The interior of the sun has a very high temperature, but even that very high temperature is not enough to make all of these things.

Do all these exotic particles exist anywhere outside of physics experiments?
They existed right after the Big Bang, when temperatures were incredibly high. And they occur in cosmic-ray events. [Cosmic rays themselves are mostly protons, but when they strike atomic nuclei in the earth's atmosphere, these rare particles can be produced.]

But when you predicted the quark in 1964, you realized it was not just another "cousin" particle, right?
That's right. Looking at the table of known particles and the experimental data, it was clear that the neutron and proton could be made up of three particles with fractional charges, which I called quarks. [Until then all known particles had charges that were a whole multiple of the charge in a proton.] Quarks were permanently confined in the neutron and proton, so you couldn't pull them out to examine them singly. The neutron and proton were no longer to be considered elementary. It was not a difficult thing to deduce. What was difficult was believing it, because nobody had ever heard of making the neutron and proton composite. Nobody had ever heard of these fractional charges. Nobody had ever heard of particles being confined permanently inside observable things and not directly attainable.

As time goes on, physicists seem to find more and more particles. Could there be an infinite number of them?
All of us theorists believe in simplicity. Simplicity has always been a reliable guide to theory in fundamental physics. But the simplicity may not lie in the number of named particles. It may be that the theory, expressed simply, gives rise to huge numbers of particle types. The particles might go on forever, but you detect only the ones that are light enough to play a role in your experiments.

Now researchers are pinning a lot of hope on finding yet another set of predicted particles in experiments at the Large Hadron Collider. Do you think this will bring some clarity?
Well, there is another possibility, that they find some phenomenon that is utterly unexpected. It would upset us if they found something totally new, totally mystifying, but that's what would be most exciting.

You were thought of as a math prodigy as a child, but math wasn't your only passion, was it?
I remember when I was around 5, I looked through my father's books. He had had a very substantial library, a huge library. And when the bad times struck—the Depression—he had to get rid of them when we moved to a tiny apartment. He had to have the furniture taken away. He couldn't sell it; he had to pay to have it removed. He paid somebody five dollars to take away his library. Heartbreaking. But he had a few books left, 50 books or something like that. One of them was a book that gave etymologies of English words borrowed from Greek and Latin. So I learned all these Greek and Latin roots and how they went to make up English words. It was exciting. That started me on etymology, and I have loved etymology ever since.

I was always OK in math. Actually I loved math, loved studying it, loved using it. I loved history. I was particularly in love with archaeology and linguistics. And I could discuss anything with my brother—archaeology, etymology, anything at all. He never did anything with it, but he was very, very intelligent and very knowledgeable about all sorts of things. He was passionate about birds and other living things. Not so much the scientific principles of ornithology, but just seeing the birds and identifying them and knowing where they were, and what kind of nest they had, and what songs they sang. Going with him on a bird trip was the best thing—the best thing—I did in those years. My brother taught me to read from a cracker box when I was 3.

When you were going into college, you were interested in studying archaeology, natural history, or linguistics, but your father wanted you to make money as an engineer.
I said I'd rather be poor or die than be an engineer because I would be no good at it. If I designed something it would fall down. When I was admitted to Yale, I took an aptitude test, and when the counselor gave me the results of the exam, he said: "You could be lots of different things. But don't be an engineer."

Then how did you settle on physics?
After my father gave up on engineering, he said, 'How about we compromise and go with physics? General relativity, quantum mechanics, you will love it.' I thought I would give my father's advice a try. I don't know why. I never took his advice on anything else. He told me how beautiful physics would be if I stuck with it, and that notion of beauty impressed me. My father studied those things. He was a great admirer of Einstein. He would lock himself in his room and study general relativity. He never really understood it. My opinion is that you have to despise something like that to get good at it.

Why is that?
If you admire it sufficiently, you'll be in awe of it, so you'll never learn it. My father thought it must be very hard, and it will take years to understand it, and only a few people understand it, and so on. But I had a wonderful teacher at Yale, Henry Margenau, who took the opposite attitude. He thought relativity was for everybody. Just learn the math. He'd say, "We'll prepare the math on Tuesday and Thursday, and we'll cover general relativity on Saturday and next Tuesday." And he was right. It isn't that bad.

You've known some of the greatest physicists in history. Whom do you put on the highest pedestal?
I don't put people on pedestals very much, especially not physicists. Feynman [who won a 1965 Nobel for his work in particle physics] was pretty good, although not as good as he thought he was. He was too self-absorbed and spent a huge amount of energy generating anecdotes about himself. Fermi [who developed the first nuclear reactor] was good, but again with limitations—every now and then he was wrong. I didn't know anybody without some limitations in my field of theoretical physics.

Back then, did you understand how special the people around you were?
No. I grew up thinking that the previous people were the special ones. Even though I knew most of them. I didn't know Erwin Schrödinger [a pioneer of quantum mechanics]; I passed up a chance to meet him for some reason. But I did know Werner Heisenberg fairly well. He was one of the discoverers of quantum mechanics, which is one of the greatest achievements of the human mind. But by the time I knew him, although he was not extremely old, he was more or less a crank.

How so?

He was talking a lot of nonsense. He had things that he called theories that were not really theories; they were gibberish. His goal was to find a unified theory of all the particles and forces. He worked on an equation, but the equation didn't have any practical significance. It was impossible to work with it. There were no solutions. It was just nonsense. Anyway, it was interesting that Wolfgang Pauli [discoverer of the exclusion principle], who did not go in for particularly crazy things—at least not in physics—was taken in by Heisenberg's stuff for a little while. He agreed to join Heisenberg in his program.

But then Pauli came to the United States, where various people worked on him—including Dick Feynman, and including me. Many of us talked to Pauli and said, "Look, you shouldn't associate yourself with this. It's all rubbish, and you have your reputation to consider." Pauli agreed, and he wrote a letter to Heisenberg saying something like: "I quit. This is all nonsense. There's nothing to it. Take my name off." In another letter, Pauli drew a rectangle on the page, and next to it he wrote: "This is to show the world that I can paint like Titian. Only technical details are missing. W. Pauli." In other words, Heisenberg had provided only a frame, with no picture. I knew Pauli fairly well. I knew Paul Dirac [another founder of quantum mechanics]. He was a remarkably eccentric person.

Of course I knew these people when they were old, not when they were young and carrying on their most important activities. But still, I knew them. And those were the people we were supposed to admire. I didn't think the people around me were going to be so special. I guess, looking back now, the era does look exciting.

There's a big difference, though, that my teacher Victor Weiskopf kept pointing out. And that is that the people who were working out the consequences of quantum mechanics, shortly after quantum mechanics was discovered in 1924 and '25, began to understand how atoms and molecules really worked, and they asked elementary questions about the world that even ordinary people might ask. For example, Victor used to say, one question is, Why can't I push one finger through the other finger? Well, ultimately it comes down to the exclusion principle [which shows that two particles cannot occupy the same space at the same time]. And so on. Whereas now you have to be sophisticated to even ask the questions that we're answering.

One of your best-known interactions was with Richard Feynman at Caltech. What was that like?

We had offices essentially next door to each other for 33 years. I was very, very enthusiastic about Feynman when I arrived at Caltech. He was much taken with me, and I thought he was terrific. I got a huge kick out of working with him. He was funny, amusing, brilliant.

What about the stories that you two had big problems with each other?

Oh, we argued all the time. When we were very friendly, we argued. And then later, when I was less enthusiastic about him, we argued also. At one point he was doing some pretty good work—not terribly deep, but it was very important—on the structure of protons and neutrons. In that work he referred to quarks, antiquarks, and gluons, of which they were made, but he didn't call them quarks, antiquarks, and gluons. He called them "partons," which is a half-Latin, half-Greek, stupid word. Partons. He said he didn't care what they were, so he made up a name for them. But that's what they were: quarks, antiquarks, and gluons, and he could have said that. And then people realized that they were quarks, and so then you had the "quark-parton" model. We finally constructed a theory—I didn't do it by myself; it was the result of several of us put together. We constructed the right theory, called Quantum Chromodynamics [QCD], which I named. [QCD describes the interactions between quarks and gluons, which bind quarks together.] And Feynman didn't believe it.

He didn't believe that the theory was correct?
No. He had some other cuckoo scheme based on his partons. Finally after a couple of years he gave up because he was very bright and realized after a while that we were correct. But he resisted it, and I didn't understand why he had to be that way. Partons...

Feynman was famously eccentric. Did you guys ever do anything wacky together?
We did lots of playful things. One of his friends was an elderly Armenian painter. My late wife Margaret and I were friendly with him too. He had some important birthday, and Margaret and I dreamed up this idea of giving him a peacock. So we conspired with the Feynmans to do it. They drew his attention somewhere else while Margaret and I got the peacock from the car and put it in his bedroom. A peacock in his bed! It's a marvelous way to give somebody a present.

Did you find it strange that Feynman became such a celebrity?
Feynman was a peculiar case because he was a very brilliant, terrific, successful scientist, but he was also a clown. He was more of a clown than he was a scientist sometimes.

But you and Feynman could get into really deep conversations about physics. You were well matched, weren't you?
For some years, and then I got fed up with him. He was just so turned in on himself. Everything was a test of his brilliance. So if in discussing things we came to some interesting conclusion, his interpretation of it was, "Gee, boy, I'm smart." And it's just annoying, so after a few years I just wouldn't work with him.

When you think about people like Feynman or Einstein or some of the other physics legends, do you think of them as geniuses? Is there such a thing?
Einstein was very special—I mean, creating that theory, general relativity [which describes gravity as a product of the geometry of space and time]. To do it today or to do it 34 years ago would be striking, remarkable, an utterly remarkable achievement. But to do it when he did, in 1915, that's just unbelievable.

When you were at the Institute for Advanced Study, Einstein was also there, although he was near the end of his life. Were you able to absorb anything from him?
I could have. I could have made an appointment with his secretary, the formidable Helen Dukas, and gone in and talked with him. I could have asked him some questions about the old days. If it were today I would do it in a moment. But all I could see then was that he was past it. He didn't believe in quantum mechanics, didn't know about the particles that we were studying. And he didn't know about this and that. If I showed him what I was doing, he wouldn't make anything of it. And if he showed me what he was doing, I wouldn't believe it. So I didn't do anything. I would say: "Hello. Good morning." And he would say, "Guten morning." That was about it.

What are you working on today?
Along with several other people around the world, I'm looking to see if there might be alternate ways to mathematically characterize entropy, the measure of disorder of a system. It might be useful to employ alternate formulas for looking at different circumstances such as financial markets or social interactions. Maybe this will turn out to be an extremely flexible tool for handling all kinds of situations. That's what people hope. Other people think it's nuts.

+

FROM THE JULY-AUGUST 2009 ISSUE

Discover Interview: Thanks, Evolution, For Making the Great Building Material Called DNA

Electronic computers are great at what they do. But to accomplish really complicated physical tasks—like building an insect—Erik Winfree says you have to grow them from DNA.

By Stephen Cass | Tuesday, August 11, 2009

RELATED TAGS: BIOTECHNOLOGY

Spencer Lowell

The humblest amoeba performs feats of molecular manipulation that are the envy of any human engineer. Assembling complex biological structures quickly and with atomic precision, the amoeba is living proof of the power of nanotechnology to transmute inert matter into wondrous forms. Amoebas—and the cells in your body, for that matter—are expert at these skills because they have had billions of years to perfect their molecular tool kit. Erik Winfree, a professor of computer science and bioengineering at Caltech, is determined to harness all that evolution-honed machinery. He is seeking ways to exploit the methods of cellular biology to create a new type of molecular-scale engineering. Although still in its early days, this line of research could lead to revolutionary ways of treating illness or creating complicated machines by growing them rather than assembling them from parts.

Winfree, who in 2000 won a MacArthur "genius grant," focuses his research particularly on DNA, the molecule that stores genetic information. Our cells use this information to build the proteins that form our bodies' structure and do nearly all the work involved in being alive. But Winfree is going beyond biology. He wants to exploit DNA's unique chemical properties to process information like a computer (using novel scientific disciplines known as molecular programming and DNA computing) and even appropriate the DNA molecule as a scaffold on which to build useful structures. Winfree spoke to DISCOVER senior editor Stephen Cass about his work, its implications for understanding the origin of life, and where this kind of research could lead in the far future.

You work in biomolecular computing. What exactly is that?

It is different things to different people. For me, it means understanding that chemical systems can perform information processing and be designed to carry out various tasks. One way I look at it is by analogy: We can design computers to perform all sorts of information tasks, and they are particularly useful when you can hook up those computers to control electromechanical systems. For instance, you can get inputs from a video camera. You can send outputs to a motor. The goal for biomolecular computing is to develop similar controls for chemical and molecular-scale systems. How can you program a set of molecules to carry out instructions?

How did you get involved in this rather exotic field of research?

I got interested in the connection between biology and computation before high school, in the early 1980s. I was just learning how to program an Apple II computer and at the same time was reading books like *The Selfish Gene* by Richard Dawkins. These things got merged in my mind. I was interested in programming biological systems—playing the games that evolution is playing. And I was interested in biological complications of all forms, particularly neural complications: How do brains work? At the same time I was developing a love for algorithms. I did mathematics and theoretical computer sciences as an undergraduate at the University of Chicago. I went to Caltech as a graduate student, interested in neural networks for robotics. Then I gave a presentation on [University of Southern California computer scientist] Leonard Adleman's work on DNA computing. It was a whole new way of thinking about the connection between molecular systems and computation. It wasn't just a theorist's playground, but an area where you could actually start having ideas for molecular algorithms and testing them in the laboratory.

You're not the first in your family to win a MacArthur fellowship—your father, Arthur Winfree, got one in 1984 for his work on applying mathematics to biology. How did his thinking influence you?

When I was growing up, he wasn't a MacArthur fellow; he was just Dad. And eccentric, maybe. He loved showing things to us kids. I developed my habit of never really just believing anything because he would always try to catch us out and make us think for ourselves. A lot of his friends that I met as a kid eventually became fellows themselves, so I grew up thinking that their original way of thinking and being was normal.

Those MacArthur connections have continued to follow you throughout your life, haven't they?

Some of that has happened by accident, and some of it not. I worked for Stephen Wolfram [an independent mathematician who created the influential Mathematica software package] for a year after meeting him at a MacArthur conference with my dad. So that wasn't by chance. But later, my Ph.D. adviser, John Hopfield, was a MacArthur fellow I met by chance, I guess because I was seeking out people I really respected. Then other people who I bumped into became fellows. I spent some time at Princeton University and met Michael Elowitz, who taught me about microscopy; he became a fellow in 2007. And there's Paul Rothemund, who was a postdoc in my lab; he got a fellowship too.

Does that sense of freewheeling community reflect the way you run your lab at Caltech?

I try to encourage a very independent attitude in my lab, partly because I know that my success is largely due to my adviser's giving me a lot of free rein. Actually, his phrase was that he gave me enough rope to hang myself. I think back to the ancient Greek philosophers and how they would meet and have a discussion where everyone brought their own story and process to the table. So when a student comes into my lab, I like to say, "OK, so come up with a project and tell me next week what you will be doing." Sometimes it's an agonizing process for them. They will take not a week but a month or a year or two years before they really figure out what they are interested in. Although that might be painful, I think it's a better process than telling people to carry out specific things where they get into a mode of not really knowing what they like.

Real biological systems use proteins to handle most jobs, but in your lab you focus on using DNA. Why?

Proteins are much more complicated than DNA. DNA is more predictable, yet it can carry out an enormous range of functions. It's sort of like a Lego kit for building things at the nanoscale; it's much easier to fit pieces together than with proteins. In a sense, we're not doing anything new. Biologists have a hypothesis that there was once an RNA world [RNA is a single-stranded cousin of DNA that acts as a translator between DNA and the protein factories in living cells]. If you look at the history of life on this planet, there was probably a time before proteins evolved. Back then RNA was both an information storage system and an active element, performing a majority of the functions within the cell. That vision tells us we can do an awful lot with nucleic acids, be it RNA or DNA.

OK, so what tasks can you accomplish with engineered DNA?
It's really exciting. We see different kinds of molecular systems as models of computation. A model of computation, to a computer scientist, is a set of primitive operations and ways of putting those primitives together to get system-level behavior.

For example, digital circuit designers have simple logic gates, such as AND and OR, as primitives. You can wire them together into circuits to do complicated functions. [Your PC operates using those commands, for instance.] But there are many different kinds of models of computation considered in computer science.

One of my main interests is in looking at what models of computation are appropriate for thinking about molecular systems. In the last four years we have gotten interested in chemical reaction networks, where you have a set of reactions: Molecule A plus molecule B reacts to form molecule C, and X plus C forms A. Traditionally, chemical reactions have been used as a descriptive language for explaining things that we see in nature. Instead, we are treating them as elements of a programming language, a way of expressing behaviors that we are trying to obtain. When you can move parts of a molecule from one place to another, it's like a computer algorithm acting on data. In the molecular world, the data structure is actually a physical structure—for example, in DNA molecules. So growing something out of DNA can be thought of as modifying a data structure. The challenge is taking a program written in that language and implementing it with real molecules—we've had some demonstrations of that, and we're very interested to see how far we can go. We also think about how to take a molecule and control it so it folds up into a very specific structure. Paul Rothemund developed that. [Rothemund made headlines in 2006 for building microscopic smiley faces out of programmed DNA.] And then there are molecular-scale motors. All of these things have been demonstrated in a primitive form with DNA systems.

That sounds fascinating from a theoretical perspective, but what are the practical implications of being able to control molecules that way?
There is a lot of excitement about intelligent therapeutics, where chemistry interfaces with biological systems to cure disease; a view based on computer science could play a role. For that kind of work, we need to distinguish among sensors, actuators, and information-processing units. At the macroscopic scale, we are familiar with the idea that sensors and actuators have to deal with the physical world, but the information-processing unit is isolated from the physical world. It's completely symbolic: zeros and ones. It doesn't care what the meaning of the zeros and ones is; it just processes them. With intelligent therapeutics there is going to be a lot of sensor and actuator work required to interface with biological systems in meaningful ways [such as detecting and manipulating molecules in order to cure disease]—that's really difficult. But the hope is that one day we will be able to build a DNA processing unit that can connect to those sensors and actuators and make decisions about what cells to target or what chemicals to produce. This is fairly speculative. I'm a long way from biomedical research myself.

What about utilizing biomolecular computing to grow devices or machines—how might that work?

Here again, the idea is that there's a part of the job that can be done by the DNA—the programmable part. And then there's a part where you need some chemically viable substance that is linked to the DNA; that is the actuator part. There is a whole set of chemistries for attaching things like proteins, carbon nanotubes, or quantum dots [5- to 10-nanometer metal dots with interesting optical properties] to DNA in specific locations. That suggests that if you can build a scaffold out of DNA, you could then chemically process it to get something useful. For example, an arrangement of carbon nanotubes bound to DNA could be turned into an electrically conductive circuit. To build that DNA scaffold, you might have it self-assemble from "tiles" made from short lengths of DNA. The tiles are designed so that they have binding rules for how they stick to each other. That is basically a programmable crystal growth process. You could put in a feed crystal containing your program [placing it into a stew of DNA tiles and other raw materials]. The feed crystal would then grow whatever object you programmed it to create.

On a philosophical level, this work is exciting because it is a purely nonbiological growth process that has many of the features we normally associate with biology. I'm so used to thinking of DNA as the ultimate biological molecule that it's hard to imagine its being used in a nonbiological way, but there is actually a long tradition of using biological components for nonbiological purposes. Like I'm sitting at a wooden desk, but trees have no intention of making desks or boats or houses or any of the things that we use wood for. So using DNA this way is completely in the human tradition for technology. It seems strange only because all our associations with DNA are biological.

When you regard DNA as a form of technology, does that change the way you look at people or at life in general?

Using DNA in this way certainly makes it possible to have a different perspective on what life is. This is a topic that philosophers often worry about, because you just can't find a satisfactory definition of life. Biologists often don't worry about it and just get on with studying it. But when you take the reductionist approach—that the phenomena we see can be explained in terms of components and how those components interact with each other—life is a mechanism, and what you look for are molecules that are capable of doing lots of interesting things. That is exactly what we found with DNA: It's a kind of information-bearing molecule that is very programmable. We can design DNA molecules to act as gates, act as motors, act as catalysts. These findings make it more plausible to view living things as software in a chemical programming language.

What is the biggest obstacle you face in turning all your amazing concepts into a reality?

I want to be able to make molecules that work the way I ask them to! For someone who is trained in theoretical computer sciences, it is difficult starting a career as an experimental lab researcher. We build and test systems, except the systems that we actually build and test are so much simpler than the systems we can write down on paper. It's one thing to make a case on paper that we can implement a 5,000-line-long set of chemical reactions with DNA. It's a different thing to build a system involving three or four reactions—and still not have it work quite the way we want it. There are many interesting things to think about at the conceptual level of how to structure programs, but at the moment we are very concerned about the implementation issue and spending most of our time there. Several issues are limiting us. For example, when we design molecular components there's all kinds of cross-talk. Our DNA-based components bump into each other. Some of the components that are not supposed to react with each other do, anyway. Certain reactions don't happen that should.

How do you plan to address those problems?
We need to build in fault tolerance. It's not clear how that will play out. One proposed reason for why biological systems are constantly making, then destroying, proteins is just so that we always have fresh molecules rather than moldy molecules on hand, which is potentially part of the solution to this cross-talk issue. Another problem is that if you have many components, they all have to be at fairly low concentrations, and at low concentrations you have very slow operations.

Are there ways to make biomolecular computing happen at the brisk pace we associate with conventional computing?
We are not going to compete with electronic computers. We're doing different things. Think about manufacturing some new kind of instrument or device that's as incredibly complicated and carefully orchestrated as a fly or an insect. To my mind, to manufacture things like that you need to grow them. Then the comparison is to biological development. If you look at the timescales in biological development, they are often hours or days. You need the right thing to happen and at the right time to grow different parts of a structure.

How long will it be before you can actually design complicated systems and therapeutic treatments with programmed DNA?
I made a plot about a year ago where I looked through influential papers in DNA computing and nanotechnology. In 1980 Ned Seeman at NYU started out the field by making a system with roughly 32 nucleotides [molecules that link together to form DNA]. If you plot the number of nucleotides people have put together since then, the growth is roughly exponential. We have a new paper that describes a system of roughly 14,000 nucleotides. The number of nucleotides in designs is roughly doubling every three years. Six more doublings—roughly 20 years from now—and we are up to a million nucleotides, which is on the order of the size of a bacterial genome. That size is not necessarily a measure of what you can do with the system, but it does tell us that in order to keep increasing at that rate we need to master complexity. We need to play the same games that computer science has been playing to handle systems that complicated. Getting these systems to work is going to be extremely challenging and will probably require real conceptual breakthroughs. Which is why I like the area.

FROM THE SEPTEMBER 2009 ISSUE

Discover Interview: Roger Penrose Says Physics Is Wrong, From String Theory to Quantum Mechanics

One of the greatest thinkers in physics says the human brain—and the universe itself—must function according to some theory we haven't yet discovered.

By Susan Kruglinski, Oliver Chanarin | Tuesday, October 06, 2009

RELATED TAGS: COSMOLOGY, STRING THEORY

Roger Penrose could easily be excused for having a big ego. A theorist whose name will be forever linked with such giants as Hawking and Einstein, Penrose has made fundamental contributions to physics, mathematics, and geometry. He reinterpreted general relativity to prove that black holes can form from dying stars. He invented twistor theory—a novel way to look at the structure of space-time—and so led us to a deeper understanding of the nature of gravity. He discovered a remarkable family of geometric forms that came to be known as Penrose tiles. He even moonlighted as a brain researcher, coming up with a provocative theory that consciousness arises from quantum-mechanical processes. And he wrote a series of incredibly readable, best-selling science books to boot.

And yet the 78-year-old Penrose—now an emeritus professor at the Mathematical Institute, University of Oxford—seems to live the humble life of a researcher just getting started in his career. His small office is cramped with the belongings of the six other professors with whom he shares it, and at the end of the day you might find him rushing off to pick up his 9-year-old son from school. With the curiosity of a man still trying to make a name for himself, he cranks away on fundamental, wide-ranging questions: How did the universe begin? Are there higher dimensions of space and time? Does the current front-running theory in theoretical physics, string theory, actually make sense?

Because he has lived a lifetime of complicated calculations, though, Penrose has quite a bit more perspective than the average starting scientist. To get to the bottom of it all, he insists, physicists must force themselves to grapple with the greatest riddle of them all: the relationship between the rules that govern fundamental particles and the rules that govern the big things—like us—that those particles make up. In his powwow with DISCOVER contributing editor Susan Kruglinksi, Penrose did not flinch from questioning the central tenets of modern physics, including string theory and quantum mechanics. Physicists will never come to grips with the grand theories of the universe, Penrose holds, until they see past the blinding distractions of today's half-baked theories to the deepest layer of the reality in which we live.

You come from a colorful family of overachievers, don't you?
My older brother is a distinguished theoretical physicist, a fellow of the Royal Society. My younger brother ended up the British chess champion 10 times, a record. My father came from a Quaker family. His father was a professional artist who did portraits—very traditional, a lot of religious subjects. The family was very strict. I don't think we were even allowed to read novels, certainly not on Sundays. My father was one of four brothers, all of whom were very good artists. One of them became well known in the art world, Sir Roland. He was cofounder of the Institute of Contemporary Arts in London. My father himself was a human geneticist who was recognized for demonstrating that older mothers tend to get more Down syndrome children, but he had lots of scientific interests.

How did your father influence your thinking?
The important thing about my father was that there wasn't any boundary between his work and what he did for fun. That rubbed off on me. He would make puzzles and toys for his children and grandchildren. He used to have a little shed out back where he cut things from wood with his little pedal saw. I remember he once made a slide rule with about 12 different slides, with various characters that we could combine in complicated ways. Later in his life he spent a lot of time making wooden models that reproduced themselves—what people now refer to as artificial life. These were simple devices that, when linked together, would cause other bits to link together in the same way. He sat in his woodshed and cut these things out of wood in great, huge numbers.

So I assume your father helped spark your discovery of Penrose tiles, repeating shapes that fit together to form a solid surface with pentagonal symmetry.
It was silly in a way. I remember asking him—I was around 9 years old—about whether you could fit regular hexagons together and make it round like a sphere. And he said, "No, no, you can't do that, but you can do it with pentagons," which was a surprise to me. He showed me how to make polyhedra, and so I got started on that.

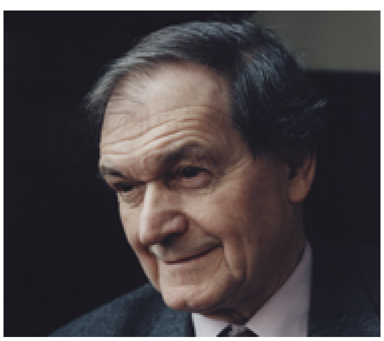
Are Penrose tiles useful or just beautiful?
My interest in the tiles has to do with the idea of a universe controlled by very simple forces, even though we see complications all over the place. The tilings follow conventional rules to make complicated patterns. It was an attempt to see how the complicated could be satisfied by very simple rules that reflect what we see in the world.

The artist M. C. Escher was influenced by your geometric inventions. What was the story there?
In my second year as a graduate student at Cambridge, I attended the International Congress of Mathematicians in Amsterdam. I remember seeing one of the lecturers there I knew quite well, and he had this catalog. On the front of it was the Escher picture *Day and Night*, the one with birds going in opposite directions. The scenery is nighttime on one side and daytime on the other. I remember being intrigued by thi

and I asked him where he got it. He said, "Oh, well, there's an exhibition you might be interested in of some artist called Escher." So I went and was very taken by these very weird and wonderful things that I'd never seen anything like. I decided to try and draw some impossible scenes myself and came up with this thing that's referred to as a tri-bar. It's a triangle that looks like a three-dimensional object, but actually it's impossible for it to be three-dimensional. I showed it to my father and he worked out some impossible buildings and things. Then we published an article in the *British Journal of Psychology* on this stuff and acknowledged Escher.

Escher saw the article and was inspired by it?
He used two things from the article. One was the tri-bar, used in his lithograph called *Waterfall*. Another was the impossible staircase, which my father had worked on and designed. Escher used it in *Ascending and Descending*, with monks going round and round the stairs. I met Escher once, and I gave him some tiles that will make a repeating pattern, but not until you've got 12 of them fitted together. He did this, and then he wrote to me and asked me how it was done—what was it based on? So I showed him a kind of bird shape that did this, and he incorporated it into what I believe is the last picture he ever produced, called *Ghosts*.

Is it true that you were bad at math as a kid?
I was unbelievably slow. I lived in Canada for a while, for about six years, during the war. When I was 8, sitting in class, we had to do this mental arithmetic very fast, or what seemed to me very fast. I always got lost. And the teacher, who didn't like me very much, moved me down a class. There was one rather insightful teacher who decided, after I'd done so badly on these tests, that he would have timeless tests. You could just take as long as you'd like. We all had the same test. I was allowed to take the entire next period to continue, which was a play period. Everyone was always out and enjoying themselves, and I was struggling away to do these tests. And even then sometimes it would stretch into the period beyond that. So I was at least twice as slow as anybody else. Eventually I would do very well. You see, if I could do it that way, I would get very high marks.



You have called the real-world implications of quantum physics nonsensical. What is your objection?
Quantum mechanics is an incredible theory that explains all sorts of things that couldn't be explained before, starting with the stability of atoms. But when you accept the weirdness of quantum mechanics [in the macro world], you have to give up the idea of space-time as we know it from Einstein. The greatest weirdness here is that it doesn't make sense. If you follow the rules, you come up with something that just isn't right.

In quantum mechanics an object can exist in many states at once, which sounds crazy. The quantum description of the world seems completely contrary to the world as we experience it.
It doesn't make any sense, and there is a simple reason. You see, the mathematics of quantum mechanics has two parts to it. One is the evolution of a quantum system, which is described extremely precisely and accurately by the Schrödinger equation. That equation tells you this: If you know what the state of the system is now, you can calculate what it will be doing 10 minutes from now. However, there is the second part of quantum mechanics—the thing that happens when you want to make a measurement. Instead of getting a single answer, you use the equation to work out the probabilities of certain outcomes. The results don't say, "This is what the world is doing." Instead, they just describe the probability of its doing any one thing. The equation should describe the world in a completely deterministic way, but it doesn't.

Erwin Schrödinger, who created that equation, was considered a genius. Surely he appreciated that conflict.
Schrödinger was as aware of this as anybody. He talks about his hypothetical cat and says, more or less, "Okay, if you believe what my equation says, you must believe that this cat is dead and alive at the same time." He says, "That's obviously nonsense, because it's not like that. Therefore, my equation can't be right for a cat. So there must be some other factor involved."

So Schrödinger himself never believed that the cat analogy reflected the nature of reality?
Oh yes, I think he was pointing this out. I mean, look at three of the biggest figures in quantum mechanics, Schrödinger, Einstein, and Paul Dirac. They were all quantum skeptics in a sense. Dirac is the one whom people find most surprising, because he set up the whole foundation, the general framework of quantum mechanics. People think of him as this hard-liner, but he was very cautious in what he said. When he was asked, "What's the answer to the measurement problem?" his response was, "Quantum mechanics is a provisional theory. Why should I look for an answer in quantum mechanics?" He didn't believe that it was true. But he didn't say this out loud much.

Yet the analogy of Schrödinger's cat is always presented as a strange reality that we have to accept. Doesn't the concept drive many of today's ideas about theoretical physics?
That's right. People don't want to change the Schrödinger equation, leading them to what's called the "many worlds" interpretation of quantum mechanics.

That interpretation says that all probabilities are playing out somewhere in parallel universes?
It says OK, the cat is somehow alive and dead at the same time. To look at that cat, you must become a superposition [two states existing at the same time] of you seeing the live cat and you seeing the dead cat. Of course, we don't seem to experience that, so the physicists have to say, well, somehow your consciousness takes one route or the other route without your knowing it. You're led to a completely crazy point of view. You're led into this "many worlds" stuff, which has no relationship to what we actually perceive.

The idea of parallel universes—many worlds—is a very human-centered idea, as if everything has to be understood from the perspective of what we can detect with our five senses.
The trouble is, what can you do with it? Nothing. You want a physical theory that describes the world that we see around us. That's what physics has always been: Explain what the world that we see does, and why or how it does it. Many worlds quantum mechanics doesn't do that. Either you accept it and try to make sense of it, which is what a lot of people do, or, like me, you say no—that's beyond the limits of what quantum mechanics can tell us. Which is, surprisingly, a very uncommon position to take. My own view is that quantum mechanics is not exactly right, and I think there's a lot of evidence for that. It's just not direct experimental evidence within the scope of current experiments.

In general, the ideas in theoretical physics seem increasingly fantastical. Take string theory. All that talk about 11 dimensions or our universe's existing on a giant membrane seems surreal.
You're absolutely right. And in a certain sense, I blame quantum mechanics, because people say, "Well, quantum mechanics is so nonintuitive; if you believe that, you can believe anything that's nonintuitive." But, you see, quantum mechanics has a lot of experimental support, so you've got to go along with a lot of it. Whereas string theory has no experimental support.

I understand you are setting out this critique of quantum mechanics in your new book.
The book is called *Fashion, Faith and Fantasy in the New Physics of the Universe*. Each of those words stands for a major theoretical physics idea. The fashion is string theory; the fantasy has to do with various cosmological schemes, mainly inflationary cosmology [which suggests that the universe inflated exponentially within a small fraction of a second after the Big Bang]. Big fish, those things are. It's almost sacrilegious to attack them. And the other one, even more sacrilegious, is quantum mechanics at all levels—so that's the faith. People somehow got the view that you really can't question it.

A few years ago you suggested that gravity is what separates the classical world from the quantum one. Are there enough people out there putting quantum mechanics to this kind of test?
No, although it's sort of encouraging that there are people working on it at all. It used to be thought of as a sort of crackpot, fringe activity that people could do when they were old and retired. Well, I am old and retired! But it's not regarded as a central, as a mainstream activity, which is a shame.

After Newton, and again after Einstein, the way people thought about the world shifted. When the puzzle of quantum mechanics is solved, will there be another revolution in thinking?
It's hard to make predictions. Ernest Rutherford said his model of the atom [which led to nuclear physics and the atomic bomb] would never be of any use. But yes, I would be pretty sure that it will have a huge influence. There are things like how quantum mechanics could be used in biology. It will eventually make a huge difference, probably in all sorts of unimaginable ways.

In your book *The Emperor's New Mind*, you posited that consciousness emerges from quantum physical actions within the cells of the brain. Two decades later, do you stand by that?
In my view the conscious brain does not act according to classical physics. It doesn't even act according to conventional quantum mechanics. It acts according to a theory we don't yet have. This is being a bit big-headed, but I think it's a little bit like William Harvey's discovery of the circulation of blood. He worked out that it had to circulate, but the veins and arteries just peter out, so how could the blood get through from one to the other? And he said, "Well, it must be tiny little tubes there, and we can't see them, but they must be there." Nobody believed it for some time. So I'm still hoping to find something like that—some structure that preserves coherence, because I believe it ought to be there.

When physicists finally understand the core of quantum physics, what do you think the theory will look like?
I think it will be beautiful.

+

FROM THE NOVEMBER 2009 ISSUE

Discover Interview: Miles of Wire, Reams of Print-Outs, and a Giant Discovery

Jocelyn Bell Burnell worked through old-school equipment and old-school sexism to find the first pulsar—the beginning of an extraordinary life in science.

By Douglas Colligan | Tuesday, December 29, 2009

RELATED TAGS: COSMOLOGY, EXTRATERRESTRIAL LIFE, STARS, DARK MATTER, LIGHT

In her calm, deliberate way, astrophysicist Jocelyn Bell Burnell has always been in the business of changing worlds. Over a storied four-decade career, she has helped expand our understanding of the universe, caused people to rethink how Nobel Prizes are awarded, and used her stature to fight sexism in the world of science.

Burnell made her first scientific mark in 1968 as Jocelyn Bell, an unknown, 23-year-old doctoral student from Northern Ireland. After months of using the new radio telescope at the University of Cambridge, she came upon inexplicable, metronomically regular radio blips from isolated spots in the sky. Bell and her Ph.D. supervisor, Antony Hewish, concluded that the blips came from hitherto unknown objects, massive yet remarkably small. Because of their pulsed signals, these objects were dubbed pulsars. Soon after, pulsars were identified as rapidly spinning neutron stars, the remnants of supernova explosions; they weigh as much as the sun but are just a dozen miles wide. The discovery was so significant that the Nobel Committee recognized it with a share of the 1974 prize in physics—an honor that was presented to Hewish but not to the young woman who had made the initial observation, Jocelyn Bell. The snub made international news.

Time magazine hyped it as "A Nobel Scandal?" But Burnell was philosophical. "I believe it would demean Nobel Prizes if they were awarded to research students, except in very exceptional cases," she later said, "and I do not believe this is one of them.... I am not myself upset about it—after all, I am in good company, am I not?"

During the 1970s and 1980s, Burnell went on to work in gamma-ray astronomy at the University of Southampton, X-ray astronomy at University College London, and infrared astronomy at the Royal Observatory in Edinburgh. In the 1990s she made a series of groundbreaking observations of the still-mysterious binary star system known as Cygnus X-3. All the while, her quiet achievements continued to break boundaries. When she became a full professor at the Open University of London in 1991, it doubled the number of female full professors of physics in the United Kingdom. In 2007 she was made a Dame of the Order of the British Emp by Queen Elizabeth in recognition of her contributions to science. Currently Burnell is a visiting professor of astrophysics at the University of Oxford; a professorial fellow at Mansfield College, Oxford; and president of the Institute of Physics in London, where DISCOVER caught up with her in her office.

Astronomy was part of your life from the beginning. Your father was the architect for the Armagh Observatory southwest of Belfast, right?
Yes. The observatory has both a 200-year-old building and newer buildings. As observatory architect, my dad was partly concerned with the maintenance of them all. I used to go with him on site visits quite often, from age 7 or 8. I have memories of crawling through the rafters of the old building, trying to find where the leak in the roof was. I probably know the rafters of that observatory better than the astronomers who worked there.

So you were involved in astronomy before you even realized it.
I don't know how much influence that had, but I clearly knew of astronomy as a subject and an occupation. When I declared an interest in it, the staff showed me the telescopes and told me what it was like being an astronomer. And they thoroughly put me off. They were optical astronomers, and they worked at night. When they said to me, a teenager who loved her bed, that you had to be able to stay up at night, I knew I couldn't. So I thought, "Hmm, maybe I can't be an astronomer." I then discovered radio astronomy and X-ray astronomy. These things were developing at that time. So I thought, "Right, then I can be a radio astronomer."

That was your prime motivation—a good night's sleep?
[Laughs.] It was a large consideration. The ironic thing is that at the point where we were discovering pulsars, I was working quite a few nights because that was when the pulsar was in the telescope beam.

And radio astronomy was so new at the time that you had to build your own radio telescope at Cambridge.
I was actually putting together the telescope. It covered four and a half acres. We put up over 1,000 posts and strung more than 2,000 dipole antennas between them. The whole thing was connected by 120 miles of wire and cable. We did the work ourselves—about five of us—with the help of several very keen vacation students who cheerfully sledge-hammered all one summer. It was a primitive type of telescope, as you would expect in the early days of the field. Radio astronomy was new then. It arose from World War II radar.

How did your radio telescope work?
The output from the telescope appeared on four three-track pen recorders as a squiggly red line on moving chart paper. The telescope produced 100 feet of chart paper every day. One complete scan of the sky took four days, or 400 feet of paper. I was responsible for analyzing this. In the six months I operated the telescope, we recorded several miles of chart.

What led to your discovery of the first pulsar?
My thesis project was to identify quasars, which are very distant, very energetic objects, and still quite mysterious. Some of the squiggles were what I was looking for, and some were radio interference. But there was another bit of squiggle that didn't make sense. It took up about a quarter-inch out of 400 feet of chart paper. I think the first few times I saw it, I noted it with a question mark. But your brain remembers things you don't realize it remembers. By about the fourth or fifth time I came across this signal, my brain said, "You've seen something like this before."

+

I talked to my supervisor, Antony Hewish. We wanted this signal not to take up just a quarter inch but to be spread out so that we could see the structure. What we needed to do was to run the chart paper more quickly. We couldn't run the chart paper at that speed for 24 hours a day—it would run out—so I had to go to the observatory each day at the appropriate time, switch to high-speed recording for five minutes, and then switch back to normal speed. I did that every day for a month. And there was absolutely nothing.

One day there was a lecture at Cambridge that I was very much interested in. I thought, "Stuff this; I'm going to the lecture." Next morning when I went out to the observatory for the routine paper change, I discovered the source had reappeared, and I had missed it. So I didn't dare go out for lunch or anything. I stayed at the observatory until that relevant time of day came and switched on the high-speed chart recording. As the chart flowed under the pen, the signal was a series of pulses. When I saw this, half of my brain was saying, "Gee whiz, it's a pulsed signal," and the other half was saying, "What do I do next?"

Was that an exciting moment?
No, it was worrying, because we were not sure what this signal was. Tony was convinced there was something wrong with the equipment. And we had to know sooner rather than later, because my whole thesis was in jeopardy. After about a month we had sorted out that it wasn't crossed wires and it wasn't interference, and it wasn't this and it wasn't that. So what was it? It kept pulsing very, very, very accurately [every 1.339 seconds]. Now, if something is going to keep pulsing regularly and it's not flagging, it must have big energy reserves. That means it's massive. But it's also small. When we say that, it's because of the rapid repetition rate—we're saying it's small in diameter. We now know that pulsars are neutron stars, which are indeed very dense. They're massive but small in dimension.

Your process of elimination is fascinating: You initially considered that the pulse could be a satellite, radio interference, a signal bouncing off a corrugated steel building?
When you're faced with something new, you have to find your own path across it, and one way is to think off-the-wall about what it might be.

Including the possibility that those pulses could be a signal beamed from another civilization?
Radio astronomers are aware in the back of their minds that if there are other civilizations out there in space, it might be the radio astronomers who first pick up the signal. It didn't make total sense, but faintly, just possibly. So we nicknamed that source Little Green Man. It was tongue-in-cheek. We weren't serious, but we had to call it something.

When did you realize what you were actually dealing with?
I was analyzing a recording of a completely different part of the sky and thought I saw some scruff. I checked

through previous recordings of that part of the sky and on occasions there was scruff there. That scruff went through the telescope beam at about 2 o'clock in the morning. So at 2 a.m. I went out to the observatory, switched on the high-speed recorder, and in came blip, blip, blip, this time one and a quarter seconds apart, in a different part of the sky. That was great. That was the sweet moment. That was eureka.

How so?
It couldn't be little green men because there was unlikely to be two lots of them on opposite sides of the universe, both deciding to signal to a rather inconspicuous planet Earth. It had to be some new kind of source, some new type of star that we had never seen before. Later I found a third and a fourth as well.

Why did the discovery of pulsars have so great an impact?
Because it was such a surprise and because the objects turned out to be so extreme. Nobody knew such things were out there. Pulsars later made black holes seem more plausible [by showing that a dying star could collapse to an extremely small size]. They opened up a whole new domain, a bit like when the Spanish conquistadores brought horses to South America. The native people had never seen horses! We had never seen anything like pulsars or neutron stars, and astronomers react not with fear—as the native South Americans did—but with excitement, delight, enthusiasm, amazement, fascination, and engagement to a startling discovery like this.

What was the response in the scientific community?
Following the announcement, every radio astronomer who had access to the right equipment was observing the known pulsars and searching for more. A lot of research projects were disrupted as radio astronomers around the world commandeered anything suitable. Within six months the optical astronomers were joining in, particularly searching for a pulsar in the Crab nebula [the remains of a nearby supernova whose explosion was seen in A.D. 1054]. A group of X-ray astronomers who had previously observed the Crab nebula reanalyzed their data to see if they could have detected a pulsar in it, and they indeed found pulsations in their data. It became clear after about six months that these pulsars were rotating neutron stars. But there are features of pulsars that we still don't understand, 40 years on. So the science moved very quickly, but it has also continued to be a lively field of research.

After the discovery was announced, you had a somewhat difficult experience with the press.
Yes, that was very…interesting. They didn't know how to handle a young woman scientist.

They asked Antony Hewish about astronomy, and they asked you if you had a boyfriend—
How many boyfriends.

—and they compared your height with Princess Margaret's.
I got rather tired of these questions about what my height and breast and waist measurements were, so I said I didn't know. Then the reporters tried prompting.

And then there was the Nobel Prize snub. Do you wonder how your life would have been different if you had won the prize?
I have discovered that one does very well out of not getting a Nobel Prize, especially when carried, as I have been, on a wave of sympathy and a wave of feminism. I also was getting a lot of other awards, to some extent in compensation for not getting the Nobel. And that's probably more fun because it means there are more parties.

The Nobel goes on a week, but there's only one party. And if you get a Nobel, nobody ever gives you anything else again because they don't feel they can match it. So getting a Nobel could well have meant less fun over all.

There was a later Nobel Prize given for pulsar work, in 1993.
Yes, the one that went to Russell Hulse and Joseph Taylor [for their work using a binary pulsar to study gravitational waves]. I went to that Nobel ceremony as one of Joe Taylor's guests.

What was that experience like?
It was great, probably more fun than going as a laureate. The recipient is forever having to stand up and say, "Thank you for this wonderful reception… [adding in a lower voice] which is totally the same as the two we had yesterday and the one we had the day before that. But never mind." [Laughs.]

How many pulsars have been found to date?
Probably pushing 2,000. It's a hugely lively field. It keeps reinventing itself into something totally different, and whoosh—we go off in another direction.

There have even been some suggestions that pulsars could someday act as guide points for interstellar travel.
Since each pulsar has its own distinct pattern of flashes and its own period, they could indeed be used one day as interstellar navigation beacons. But not yet, because we would need to attach a 100-meter [300-foot] radio telescope to a spaceship—or attach a spaceship to a 100-meter telescope. Some technological advances are required. Pulsars also provide us with very accurate clocks distributed through the galaxy, swinging beams around the sky like lighthouses and doing so with incredible precision. They have opened up experimental, as opposed to theoretical, ways to test Einstein's theories of relativity. So far, the theories have checked out, but the pulsar astronomers are not done yet.

You have spoken often about the "leaky pipeline" phenomenon, referring to women who drop out of science careers after getting their Ph.D.s. Was there a time when you thought you might become part of the leak?
Oh, yes, a lot of times, particularly during the phase when I was married and raising a family and following my husband around the country as he changed jobs. At the point when our son was born, I assumed I would suddenly turn into a normal female and would be quite happy staying at home and looking after a baby. I rapidly discovered that this assumption was wrong. To some extent I was trapped, in that I didn't have a regular job. So I got a part-time tutoring job.

You tell an anecdote about how the Royal Astronomical Society was doing a series of lectures on British astronomers and did not want to include the 18th-century astronomer Caroline Herschel because she wasn't good-looking enough.
That's right. [Sighs.]

Did this happen recently?
Not that long ago. And all my generation of women scientists have a host of stories about those kinds of thing. In Britain, in generations older than me, women were not expected to have careers. In generations younger than me, women do expect to have careers, or at least the option to have a career. It's my generation that has been the turning point, and being at the turning point can be a bit rough sometimes.

What made you decide to speak out on the challenges facing women who want to have careers in science?
I can remember when I was a full professor at the Open University, suddenly realizing that I was probably secure enough, established enough, that I could afford to start making trouble, thinking about other women and not just about my own career. I could start rattling the bars of cages. That was a very conscious decision, probably about 10 years ago.

What's happening now is there is progress, although it's slower than any of us would have wished. That may be just because we were too optimistic. And the other thing that's happening at the moment is that four or five of the professional scientific and engineering bodies have suddenly got female presidents. The Geological Society has a female president. The Institute of Physics does too, and three of the engineering ones have or are about to have. I would love to think that the tide has turned.

Clearly, instead of being part of the leaky pipeline, you found your way back into the research world.
Yes, but note that a number of my positions have been management, not typical academic ones. For example, at the Royal Observatory Edinburgh I headed the James Clerk Maxwell Telescope Section. I was also chair of the country's biggest physics department at the Open University, and I was the dean of science at Bath.

On the research side of your work, what is the most exciting thing you have studied since your pulsar days?
After pulsars, the research I am proudest of is on an X-ray source called Cygnus X-3, the third X-ray source discovered in the constellation of Cygnus. It is an X-ray emitting binary star near the edge of our galaxy, about 30,000 light-years away.

Some astronomers think Cygnus X-3 is a regular star orbiting a neutron star or a black hole. But nobody is really sure, is that right?
Right. Infrared observations have shed some light on this obscure object. It shows bizarrely unique behavior in all wavelengths and appears to expand and contract at speeds greater than the speed of light. [The apparent faster-than-light speed, also seen in some quasars, is believed to be an illusion caused by our perspective on the object.]

In 1999 you singled out dark matter as one of the greatest mysteries in astrophysics. What do you think about it now, a decade later?
[Laughs.] I'm still saying that. I have been saying for some time that we need a paradigm shift in cosmology, and I'm not alone in thinking it. But who knows what this new thing is If we knew, we would have Nobel Prizes right, left, and center. Cosmology does seem, to me, to be getting messy and is ripe for a change.

Do you think there is a revolution in the offing?
Well, I think it's due. Whether it's in the offing is another question.

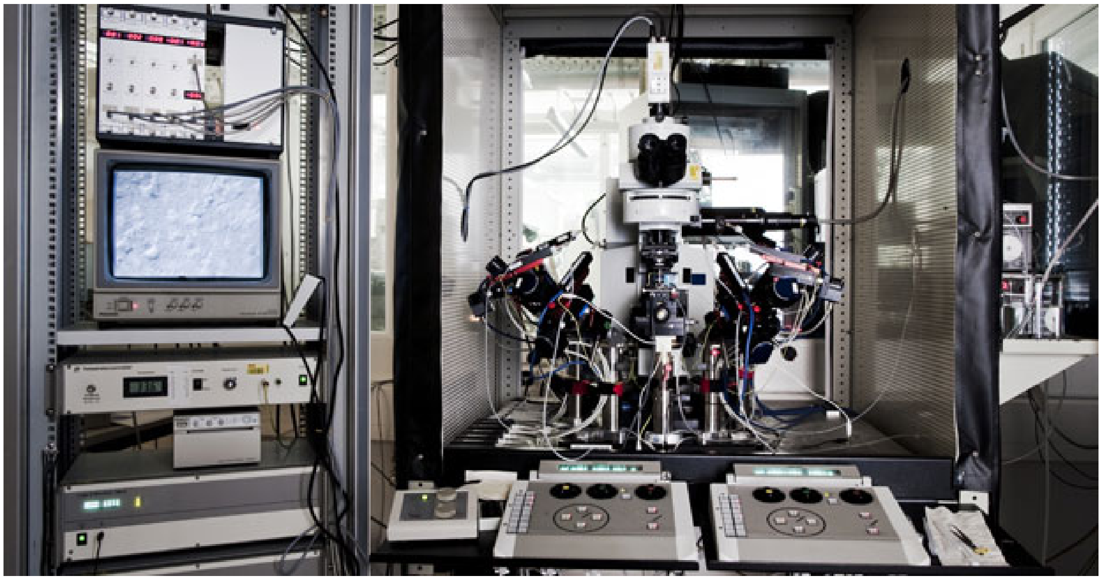
FROM THE DECEMBER 2009 ISSUE

Discover Interview: The Man Who Builds Brains

Using computer processors that behave like neurons in the neocortex, Henry Markram is inching closer to building a simulated human brain—a truly conscious machine.

By David Kushner | Friday, February 05, 2010

RELATED TAGS: MACHINE-BRAIN CONNECTIONS, COMPUTERS, MEMORY, EMOTIONS, & DECISIONS



Photograph by Robert Huber

On the quarter-mile walk between his office at the École Polytechnique Fédérale de Lausanne in Switzerland and the nerve center of his research across campus, Henry Markram gets a brisk reminder of the rapidly narrowing gap between human and machine. At one point he passes a museumlike display filled with the relics of old supercomputers, a memorial to their technological limitations. At the end of his trip he confronts his IBM Blue Gene/P—shiny, black, and sloped on one side like a sports car. That new supercomputer is the centerpiece of the Blue Brain Project, tasked with simulating every aspect of the workings of a living brain.

Markram, the 47-year-old founder and codirector of the Brain Mind Institute at the EPFL, is the project's leader and cheerleader. A South African neuroscientist, he received his doctorate from the Weizmann Institute of Science in Israel and studied as a Fulbright Scholar at the National Institutes of Health. For the past 15 years he and his team have been collecting data on the neocortex, the part of the brain that lets us think, speak, and remember. The plan is to use the data from these studies to create a comprehensive, three-dimensional simulation of a mammalian brain. Such a digital re-creation that matches all the behaviors and structures of a biological brain would provide an unprecedented opportunity to study the fundamental nature of cognition and of disorders such as depression and schizophrenia.

Until recently there was no computer powerful enough to take all our knowledge of the brain and apply it to a model. Blue Gene has changed that. It contains four monolithic, refrigerator-size machines, each of which processes data at a peak speed of 56 teraflops (teraflops being one trillion floating-point operations per second). At $2 million per rack, this Blue Gene is not cheap, but it is affordable enough to give Markram a shot with this ambitious project. Each of Blue Gene's more than 16,000 processors is used to simulate approximately one thousand virtual neurons. By getting the neurons to interact with one another, Markram's team makes the computer operate like a brain. In its trial runs Markram's Blue Gene has emulated just a single neocortical column in a two-week-old rat. But in principle, the simulated brain will continue to get more and more powerful as it attempts to rival the one in its creator's head. "We've reached the end of phase one, which for us is the proof of concept," Markram says. "We can, I think, categorically say that it is possible to build a model of the brain." In fact, he insists that a fully functioning model of a human brain can be built within a decade. Markram spent some time with DISCOVER to explain how.

Most people—even most scientists—still regard the brain's inner workings as a mystery. Yet you believe not only that you can understand the brain but that you can, in effect, re-create it. What do you see that others do not?
Everybody agrees that the brain is a remarkable machine. It's capable of generating an enormous number of phenomena, some of them very obvious and some of them less obvious. But I think that in the end there are going to be some very basic explanations for many things: emotions, awareness, consciousness, attention, perception, recognition. We have to address a couple of fundamental problems, but I see them as problems only because we are stuck in two old paradigms of thought.

What are the outmoded paradigms that we need to get past?
The first is related to how the brain represents information, what I call an action-potential paradigm. It's a spike-based paradigm. Neurons generate spikes of activity. You can think of these spikes as digital: zeros and ones. Individual spikes do not have enough information to represent perceptions. The current view of perception is based on analyzing these zeros and ones and trying to decompose or reverse engineer the representation that these zeros and ones capture. But I think that the zeros and ones—the information generated or emitted by single neurons—are a reflection of perception, not perception itself.

A lot of people study these single spikes. What we have been working on with Blue Brain is like a Copernican revolution, because we want to flip things around and say that neural representation does not lie in the spikes. It lies in the branches beyond, before it gets to the cell body. When this new way of thinking starts to take hold, I think it will open up a lot of doors into what perception is—and from perception what recognition is, and from recognition what memory is, and then higher functions, such as awareness or emotions.

What is the other big misconception that's holding us back?
For 50 years we've been thinking of memory, despite all evidence to the contrary, as where you imprint changes in the brain. You go to your synapses, you go to your neurons, and you change them when you remember something. And then you've got to protect those changes. It's an imprint. It's called an engram. Hundreds of scientists have been chasing this engram. Where is the print of memory in the brain? They think it's like a scar, a mark. This is one of the most fundamental mistakes in neuroscience. And the reason why I say it's a mistake is simple. All evidence indicates that the neuron does not reset. The synapses do not reset. They are always different. They're changing every millisecond. Your brain today is very, very different from what it was when you were 10 years old, and yet you may have profound memories from when you were 10. What has to be answered in neuroscience is this: How do you remember something from long ago when your brain now is actually different?

We have had too many physicists move into neuroscience and say, "Oh, it must be some kind of statistical distributed memory, so even if it's overwritten there will still be some traces of it." In our view, the idea that memory is held in the brain the same way it is held in a computer is fundamentally wrong.

So those are the two paradigms that we're stuck in. I think that cracking them is going to change a lot of things about the mystery of the brain.

Photograph by Robert Huber

How can a simulation crack the mystery of the brain? Don't you need to understand it before you can simulate it?

To understand how a protein behaves in the context of a whole brain, you're going to need to put it into a whole brain. You're going to need to play with it, change its parameters, take it out, put it in, make a mutation. We need the flexibility to be able to explore thousands, hundreds of thousands, millions of parameters. A model is one way to do it—but not the kind of model that people have been using. I'm talking about real, biologically constrained models. The most serious misconception about Blue Brain is that people think we're doing a modeling project. Actually Blue Brain is very much about reverse engineering, looking at all the data, standardizing the data, getting the information into a framework where we can even do correlation-based science on it, building automatic tools to synthesize those data into biological phenomena. I think of the process as virtualizing life, virtualizing the brain.

How do you even approach such a huge and radical project?

Before we did this, it was a three-year Ph.D. project to simulate even one neuron. And you needed an entire, very powerful computer to run that simulation of one neuron. You needed the whole process. Of course, today computers are a little more powerful, and I can run a simulation of 100 neurons. But there's really no point in doing a 100-neuron simulation. The reason is simple: A neuron lives in an environment. It receives thousands of inputs. So actually you need to make a quantum leap from one neuron to 10,000 neurons. You need to make that leap into what we call a microcircuit. A circuit of five neurons is not what the mammalian brain is made up of. To simulate the neurocircuitry that is creating the mammalian brain, you need to make a quantum jump in complexity. You need at least 10,000 computers to do that. And that's what Blue Gene is—16,000 processors squeezed into a space the size of four refrigerators. It was important for us to have that many processors, because on each one we've got 1,000 neurons. The processors themselves did not have to be extremely powerful. They just needed enough memory to hold the neurons.

+

You are modeling not a human brain or a monkey brain but something very specific—the neocortical column in a two-week-old rat. Why that particular set of neurons?
Blue Brain is a bio-driven project, meaning that we work to capture the biological elements, processes, and principles as mathematical models, and then run simulations to see how they mimic biology. We are trying to re-create biology in software as accurately as possible. I was not prepared to sacrifice a lot of cats or primates—this research requires dissecting brains and comparing the simulation to the real thing—so we had to choose either mice or rats. Then it was a question of which brain region to focus on. Even though the neocortex is the most advanced region, it's got more order and organization and therefore actually is more tractable. If you go into the brain stem or into other subcortical areas of the brain, the neurons have no distinguishing features. They're all kinds of shapes. A two-week-old animal is ideal, actually, because at that stage slices of the brain preserve extremely well for 24 to 48 hours. The circuit at that age is going to be in 75 to 80 percent of the final state it will be in during the adult stage. What it gives us is the template for brain circuitry. Once we have the template we look for variations, and then we can model development. We can now model younger columns, and we can model older columns. When we find out the key differences between species, we will be able to start simulating and modeling evolution, too.

Your experiment has been going on for more than four years now. What have you learned so far about the neural processes in the brain?
One very interesting property that emerged is a rhythm of electrical activity called gamma oscillations. It appeared one week when we added in the step of biological simulation. We did not try to build it in—it just showed up. Gamma oscillations are the basis for consciousness, according to a famous theory. The theory holds that when the brain goes into high-frequency (40- to 80-hertz) oscillations, those oscillations do perceptual binding, which is the foundation of consciousness. I don't think that Blue Brain is conscious at this point, though.

It's significant that we didn't specifically try to model the phenomenon in the brain. All we have to do is pay attention to the fact that we are building it correctly, and these phenomena emerge. The whole circuit goes into this resonant state, which is an amazing state. Now we can dissect the circuit and find out exactly which neurons were crucial, which pathways, which receptors, and so forth.

As we've taken steps closer to the biology, the circuit has started to display more and more of the actual biological phenomena that we find in experiments, with more and more precision and accuracy and elegance. This is very encouraging because the model could have gone in any other direction. It could have just not worked. As you put in more and more fine-tuned parameters, it might start doing all kinds of things you would not want or expect it to do.

Can you also use Blue Brain to help with medical problems—to study the nature of neurological diseases?
Actually, this is the only way to study them. When you turn on this column and you run it, you think, my God, there's not a single neurological disease today in which anybody knows what is malfunctioning in this circuit—which pathway, which synapse, which neuron, which receptor. Doctors don't even know this for a single drug—I mean, this is a multibillion-dollar industry!—that they're giving for Parkinson's disease, for depression, schizophrenia, attention deficit, autism, dementia, Alzheimer's. When they give a drug, they have no idea what it does to this processor. And the neocortical column is the elementary processor for human beings to have

coherent perception, attention, and memory. This is shocking. I mean, we are living in such a primitive time of medicine, you cannot imagine.

How could your work fill in the missing understanding?
If you have the model where you're able to embody all the key parameters, you can start exploring a hypothesis for a disease. When you tweak the model, you can see what kind of pathology occurs. You'll be able to really isolate very precisely what has gone wrong. If a certain part of the circuit malfunctions, it's going to display certain symptoms. You can actually simulate and test hypotheses for different diseases. If we know which pathways are malfunctioning, then we can look and see what it means for the circuit, what kind of information is it not able to process. This can guide drug discovery by letting you simulate the effect of a drug on the circuit. You're going to find out exactly how it operates, what it is altering. Drug discovery is terribly expensive, just to find out how one drug could or could not work and all its side effects. Simulations could cut drug discovery costs by 70 or 80 percent. What we call in-silica-based drug discovery—simulation-based drug discovery—is going to be the future.

How soon could simulated brains lead to new drugs for treating our real brains?
We're already at prototype stage. We can already start on a limited scale. But I think this is coming within the next two or three years. As the model gets more powerful, its reach will spread to more and more domains of neurology and psychiatry.

What are the next great milestones for the Blue Brain project? In particular, when will you be able to simulate a human brain, not just a section of rat brain?
It's a question of scaling, and it's a question of resolution. The next phase is going to be a massive expansion toward whole-brain models, and also toward very detailed molecular-level models. Technologically, in terms of computers and techniques to acquire data, it will be possible to build a model of the human brain within 10 years. Practically, the only limitation is funding. But we are taking this step by step. The next step should take us in three years to a whole-brain model of a rat and a detailed molecular-level model of the interactions of the 200 million neurons in a rat's brain. That's going to provide most of the key stepping-stones to be able to do the next jump to cat, primate, and human brain models, which will happen pretty much in parallel.

One of the most important things we have realized in this project is that you don't need to know 100 percent of how the biology works. Because after you put in the data for 5 percent or 10 percent, it starts constraining almost everything else. Which means you can actually learn the rest without knowing what it was before, so in the end it just gets faster. As you add more constraints, it's like an acceleration. My prediction is that we will understand the brain, its design and function, way before we finish building it.

If it really is mainly a matter of money to build a full simulation of the human brain, how much money would it take?
A lot. More than the Human Genome Project, much more. There are the supercomputers that are required. And you need the researchers, because it's not only us, it's a consortium that is going to have to grow enormously. The computers alone would cost hundreds of millions of dollars, maybe even a billion dollars. Then you need the data that describe the brain's composition and structure—such as the number of proteins in the brain, what kind they are, how they interact, the density of cells. The data need to come much more from industry, not just from science labs. We need to get industrial-scale data, and actually that's going to be an enormous cost.

+

What then? Once we model the human brain, will we be able to experience and re-create what goes on in a person's mind?
It's not really very complicated. In order for me to read your thoughts, I need to be able to look at your patterns, and I need to be able to convert them into a readout. I have to be able to translate that activity. That is the neural code. I need to understand it and to read it, decode it.

As we become better at decoding the neural information, I think that will not be such a big deal. If we can extract information, it's more of a technological limitation. Can you extract it? Can you get enough sampling? Can you measure the activity state? The technology for doing these things is improving a lot. We are very close to the neural code. All indications are that it will improve a lot in the next couple of years.

Will we be able to simulate consciousness at that point? Or the even more staggering question—will the simulation actually be conscious at that point?
It's really difficult to say how much detail is needed for consciousness to emerge. I do believe that consciousness is an emergent phenomenon. It's like a shift from a liquid to a gas. It's a property. It's a new phase. It's like a machine that has to run fast enough and suddenly it's flying. That's what, in this project, we'll be able to perhaps find out—how much detail is needed for the machine to really take off and become conscious.

Some people have said that you are playing God. Do you ever feel that way?
As scientists we need to not be afraid of the truth. We need to understand our brain. It's natural that people would think that the brain is sacred, that we shouldn't tamper with it because it may be where the secrets of the soul are. But I think, quite honestly, that if the planet understood how the brain functions we would resolve conflicts everywhere. Because people would understand how trivial and how deterministic and how controlled conflicts and reactions and misunderstandings are. Where did these behaviors come from? The answer is understandable and tractable and traceable. We shouldn't die for certain things that may well just be because of a chemical firing off in one part of the brain.

I think that understanding the brain is going to be an enormously great awakening. It could well be a crucial thing for humanity. I think that we're far from playing God. God created the whole universe. We're just trying to build a little model.

+

FROM THE EXTREME UNIVERSE 2010 ISSUE

The Man Who Plucks All the Strings

Brian Greene says string theory is still scientific even if it's not falsifiable.

By Andrew Grant | Tuesday, March 09, 2010

RELATED TAGS: STRING THEORY, SUBATOMIC PARTICLES

This article is a sample from DISCOVER's special Extreme Universe issue, available only on newsstands through March 22.

photography by Jennifer Karady

In the 1960s, Italian physicist Gabriele Veneziano developed a theory to explain the inner workings of the atom and failed—at first. Now many scientists believe an improved version of his conjecture, known as string theory, may do more than merely explain the atom. It could be the elusive theory of everything, a set of universal laws governing everything from the smallest quark within the atom to the largest cluster of galaxies, from the Big Bang to this moment.

String theory explains what you might see if you zoomed in without limit, past the cells that constitute your body, past the atoms that make up those cells, past even the electrons and gluons that those atoms are made of, all the way to the scale of a billionth of a trillionth of a trillionth of a centimeter. At that level, according to the theory, lies the foundation of all the particles and forces in the universe: one-dimensional strands of energy, or “strings,” vibrating in nine dimensions. That may seem wildly counterintuitive, but many scientists agree it is the most promising approach to explain the laws of physics.

Columbia University physicist Brian Greene has become the public face of string theory. He has provided insight into the topology of those additional dimensions, and in 1999 he introduced the theory to nonscientists in a best-selling book, *The Elegant Universe*. In 2008 he cofounded the World Science Festival, an annual event that brings together scientists, artists, and ordinary people who are simply interested in the great questions of the universe. Greene talked to DISCOVER about how string theory has evolved, the attempts to find supporting evidence through new experiments, and the challenges of making science exciting to the general public.

What is the major problem string theory attempts to solve?

Our current theory of gravity—Einstein’s general theory of relativity—and our current theory of the behavior of atoms and subatomic particles—quantum mechanics—both work fantastically well in their respective domains: general relativity for big things, quantum mechanics for small things. But when you try to meld the two, there is an incompatibility, a hostility. It’s uncomfortable to have two laws of physics, each claiming that the other somehow doesn’t work. In reality, both sets of laws are meant to work everywhere.

How does string theory create a single worldview that applies everywhere—and what exactly is a string, anyway?

The fundamental idea is that the elementary constituents of matter—electrons, quarks, and so forth—might not be dots of no size, which is the traditional image, but rather little filaments. They could exist in either little loops of filament—tiny loops of energy—or little snippets of energy, open strings as we call them. When people stared at the mathematics governing the motion of these little filaments, they found, remarkably, that the math didn't work in a universe that has only three dimensions of space. It required nine dimensions, and when you add in time it gives you 10 dimensions, which is an astoundingly bizarre idea. Nevertheless, it's an idea that string theorists take seriously, because that's where the math leads, and math has proved itself to be a very sure-footed guide to how the universe works.

How can we envision these extra dimensions, and how would they manifest themselves in our seemingly three-dimensional world?

The shape and size of the extra dimensions would affect the properties of particles. So if you asked me, "Why does the electron have its charge or its particular mass?" the answer in string theory would be because the extra dimensions have the shape that they do. An electron weighs what it does because it has a certain internal energy, and that energy, according to Einstein, equals mc^2. The energy depends on how its little string can vibrate, and the string vibrates in a manner that depends on its environment, so it depends on the shape of the extra dimensions. The dream in the 1990s was to find the shape of the extra dimensions and then calculate the values of all those properties that experimenters have found.

What is the current status of string theory research?

We have a range of possibilities for the shape of the extra dimensions. We have, in fact, catalogs of shapes. Literally, I could write out a book and turn page by page and show you different shapes for the extra dimensions that people have mathematically determined as being possible. The problem is we don't know which page is the right one, and the number of pages has grown fantastically in the last few years. There are on the order of at least 10^{500} different pages now [a number that dwarfs the number of particles in the universe], and when you're faced with a book of that many pages, some people throw up their hands in disgust. Others say that maybe all those shapes are out there in different universes. That's the most recent and controversial approach that people have been following.

So there could be a multitude of other universes, each corresponding to a different solution or "page" of string theory?

As scientists we track down all promising leads, and there's reason to suspect that our universe may be one of many—a single bubble in a huge bubble bath of other universes. And you can then imagine that maybe these different bubbles all have different shapes for their extra dimensions. This suggests a landscape of different universes with different forms of extra dimensions and therefore different properties within those universes. If that is true, our universe would be one of many, and then the question becomes why are we in this one and not in some other one.

One of your findings is helping scientists make sense of those extra dimensions and other universes, right?

We found that classical geometry, the kind you learn in elementary school, breaks down at extremely small scales. Instead, quantum geometry takes over, in which, for example, there can be two very different shapes in the extra dimensions that nevertheless yield exactly the same physics. In other words, there can be two different shapes from the perspective of a classical mathematician, but when dressed up with their quantum properties they become identical. What got us really excited was that horrendously complicated calculations framed in the language relevant to one shape became simple when reframed using the other shape. People like to talk about the Eskimos' having 20 terms for snow and ice. It might take us a paragraph or a book to try to describe those distinctions, because our language is not set up to describe them. Similarly, with these shapes we're basically rephrasing things from one language to another, and suddenly some very clunky and cumbersome descriptions become sleek, elegant, and completely solvable.

Critics of string theory have called it unscientific because it is not falsifiable. How can we evaluate string theory?

Falsifiability for a theory is great, but a theory can still be respectable even if it is not falsifiable, as long as it is verifiable. There are aspects of a theory that you can go out and look for and confirm, and that's another way to gain confidence in it. For instance, it's really hard to falsify the statement that there is life on another planet, but you can verify it by finding one example. We're hoping that certain features of string theory are confirmable.

What kind of things are you looking for?

At the Large Hadron Collider in Geneva, there are features of string theory that may result in data that have no other natural explanation. For instance, string theory suggests that there should be a class of particles called supersymmetric particles [that every particle should have a partner particle], and we've never seen them before. If we see them, it won't prove string theory right, but it would be a strong piece of circumstantial evidence, because their most natural home is in string theory. There's also a long-shot chance that scientists will find evidence for extra dimensions at the LHC. String theory is not the only theory that can accommodate extra dimensions, but it certainly is the one that really demands and requires it.

How are physicists trying to find extra dimensions?

When two protons collide, as they will be doing quite frequently in the LHC, some of the debris created from the collision might be ejected out of our familiar dimensions and crammed into the others. We could notice that by detecting missing energy in our dimensions. The energy would seemingly disappear, but in reality it would just go to a place that our detectors don't have direct access to.

If today you somehow found out that string theory is wrong, how would you feel about all your work of the past 25 years?

If it was false by virtue of an actual error that we all overlooked for 25 years, I'd feel pretty bad. But that's so unlikely—nearly impossible, I'd say. The more likely thing is that we'll learn that the theory is perhaps incapable of describing physics as we know it. The bottom line is progress, and if we can understand why it is that string theory failed, that will be progress. It won't be the progress that we had hoped for, but it will be progress nevertheless, and that's how science works.

How confident are you that string theory is correct?

One time I was listening to a radio program and I was described as a believer in string theory. I almost hit the roof because I don't "believe" in string theory. I don't believe in anything until it's experimentally proven. I do feel strongly that string theory is our best hope for making progress at unifying gravity and quantum mechanics. Moreover, I've been spectacularly impressed over the past 20 years with the progress that string theory has made. But that's not proof, and therefore I don't believe it. There are a lot of very interesting ideas that are worthy of attention, and sometimes worthy of decades of attention, because they have such capacity to make progress on deep, unsolved questions. But that doesn't mean that you believe the ideas are right. If you want to use the word belief, I simply *believe* that this is the best approach that we have.

You are the author of a best-selling book and the cofounder of a popular science festival. How do you go about getting people interested in something as esoteric as string theory?

I think many people had experiences in school where science was about learning details or completing rigorous calculations that may not have aligned with their personality. What gets missed is that those details are ultimately used by science to address big questions that we all care about: Where did the universe come from? Where did life come from? Will it all eventually come to an end? I think students often, by virtue of the way we teach, miss the big story and are led through the gritty details, leaving a bad taste in the mouth. Tracy Day and I created the World Science Festival to go around existing structures and create a place where people, led by real scientists, could immerse themselves in science's great stories and big ideas. Don't get me wrong, the details are important, but people will never want to know the details unless they can focus on the big ideas.

This article is a sample from DISCOVER's special Extreme Universe issue, available only on newsstands through March 22.

FROM THE APRIL 2010 ISSUE

It's Gettin' Hot in Here: The Big Battle Over Climate Science

Two eminent climatologists share much different views: Michael Mann—whose private emails were hacked—points a finger at skeptics. Judith Curry believes humans are warming the planet but criticizes her colleagues for taking shortcuts.

By Fred Guterl | Wednesday, March 10, 2010

RELATED TAGS: GLOBAL WARMING, ENVIRONMENTAL POLICY

Where does climate science go from here? The Copenhagen talks were a dud. Stolen e-mail correspondence has embarrassed some leading climatologists. If the science is settled and the threat is urgent, why has global warming become a soap opera? To find out, DISCOVER sought two different, important views, from Penn State's Michael Mann and Georgia Tech's Judith Curry.

What was your reaction to the scandal over stolen e-mail?

I sympathize a bit with the guys who got caught out in the e-mail hack. I know what it's like to be under that kind of attack, and it's not pleasant. We were attacked pretty soundly in the media [for a 2005 paper showing that the frequency of intense hurricanes has almost doubled in the past 30 years]. We had firsthand experience dealing with climate skeptics, amplified by advocacy groups like the Competitive Enterprise Institute and a lot of the think tanks that were allegedly funded by ExxonMobil and other firms. Six months later, though, we had sorted things out and were talking to scientists on the other side of the debate. We ended up making pretty good progress on the hurricane story as a result. Compare that with the "hockey stick" story, where there's been a war for six years running.

Judith Curry heads the Georgia Tech School of Earth and Atmospheric Sciences. *Photography by Imke Lass*

The hockey stick—Michael Mann's widely cited graph of average temperatures in North America over the past 1,000 years—was attacked by two prominent critics, Steven McIntyre, a former mineral company executive, and Ross McKitrick, an economics professor at the University of Guelph in Canada. Where does that dispute stand?

One would have hoped it would have an outcome similar to the hurricane story, but the hockey stick thing was exacerbated by Michael Mann's behavior, trying to keep the data and all the information away from McIntyre, McKitrick, and other people who are skeptical of what they were doing. So we've just seen this blow up and blow up and blow up, and it culminated in the East Anglia hack and the e-mails that discredited those guys quite a bit. This made us reflect on the bigger issues of how scientists should be interacting with the media and how we should be dealing with skeptical arguments. I think the way that Mann and Phil Jones [the former director of the Climatic Research Unit at East Anglia, who resigned over the scandal] and those guys were going about it was wrong, not just in terms of ethics. It also backfired.

What motivated you to speak out?
When this hit, I was probably more ready than many others to respond because I'd been thinking about these issues for a number of years.

Do you find it hard to get people to talk about climate change without being evangelical?
I put myself in the middle, and I'm taking fire from both sides. Neither side is happy with what I'm doing. Obviously, people like Michael Mann are offended by what I'm saying [about the shortcomings of climate science], and I have received an e-mail from one of the people involved in the East Anglia e-mails who's not happy with what I'm doing. The so-called skeptics think I'm just trying to cover myself. But I'm not personally involved in any of this, other than that I've been thinking about these issues for a long time, and there are certain things I felt compelled to say.

Where do you come down on the whole subject of uncertainty in the climate science?
I'm very concerned about the way uncertainty is being treated. The IPCC [the United Nations' Intergovernmental Panel on Climate Change] took a shortcut on the actual scientific uncertainty analysis on a lot of the issues, particularly the temperature records.

Don't individual studies do uncertainty analysis?
Not as much as they should. It's a weakness. When you have two data sets that disagree, often nobody digs in to figure out all the different sources of uncertainty in the different analysis. Once you do that, you can identify mistakes or determine how significant a certain data set is.

Is this a case of politics getting in the way of science?
No. It's sloppiness. It's just how our field has evolved. One of the things that McIntyre and McKitrick pointed out was that a lot of the statistical methods used in our field are sloppy. We have trends for which we don't even give a confidence interval. The IPCC concluded that most of the warming of the latter 20th century was very likely caused by humans. Well, as far as I know, that conclusion was mostly a negotiation, in terms of calling it "likely" or "very likely." Exactly what does "most" mean? What percentage of the warming are we actually talking about? More than 50 percent? A number greater than 50 percent?

Are you saying that the scientific community, through the IPCC, is asking the world to restructure its entire mode of producing and consuming energy and yet hasn't done a scientific uncertainty analysis?
Yes. The IPCC itself doesn't recommend policies or whatever; they just do an assessment of the science. But it's sort of framed in the context of the UNFCCC [the United Nations Framework Convention on Climate Change]. That's who they work for, basically. The UNFCCC has a particular policy agenda—Kyoto, Copenhagen, cap-and-trade, and all that—so the questions that they pose at the IPCC have been framed in terms of the UNFCCC agenda. That's caused a narrowing of the kind of things the IPCC focuses on. It's not a policy-free assessment of the science. That actually torques the science in certain directions, because a lot of people are doing research specifically targeted at issues of relevance to the IPCC. Scientists want to see their papers quoted in the IPCC report.

You've talked about potential distortions of temperature measurements from natural temperature cycles in the Atlantic and Pacific oceans, and from changes in the way land is used. How does that work?
Land use changes the temperature quite a bit in complex ways—everything from cutting down forests or changing agriculture to building up cities and creating air pollution. All of these have big impacts on regional surface temperature, which isn't always accounted for adequately, in my opinion. The other issue is these big ocean oscillations, like the Atlantic Multidecadal Oscillation and the Pacific Decadal Oscillation, and particularly, how these influenced temperatures in the latter half of the 20th century. I think there was a big bump at the end of the 20th century, especially starting in the mid-1990s. We got a big bump from going into the warm phase of the Atlantic Multidecadal Oscillation. The Pacific Decadal Oscillation was warm until about 2002. Now we're in the cool phase. This is probably why we've seen a leveling-off [of global average temperatures] in the past five or so years. My point is that at the end of the 1980s and in the '90s, both of the ocean oscillations were chiming in together to give some extra warmth.

If you go back to the 1930s and '40s, you see a similar bump in the temperature records. That was the bump that some of those climate scientists were trying to get rid of [in the temperature data], but it was a real bump, and I think it was associated with these ocean oscillations. That was another period when you had the Pacific Decadal Oscillation and the Atlantic Multidecadal Oscillation chiming in together. These oscillations and how they influence global temperature haven't received enough attention, and it's an important part of how we interpret 20th-century climate records. Rather than trying to airbrush this bump in the 1940s and trying to get rid of the medieval warm period—which these hacked e-mails illustrate—we need to understand them.

They don't disprove anthropogenic global warming, but we can't airbrush them away. We need to incorporate them into the overall story. We had two bumps—in the '90s and also in the '30s and '40s—that may have had the same cause. So we may have exaggerated the trend in the later half of the 20th century by not adequately interpreting these bumps from the ocean oscillations. I don't have all the answers. I'm just saying that's what it looks like.

What about risk? Isn't it worth heading off even a small risk of catastrophe?
Oh, absolutely.

How does the lack of uncertainty analyses affect the calculation of risk?
You can think of risk as what can happen multiplied by the probability of its actually happening. The IPCC gives the whole range of things that could happen, some that involve a small amount of warming and some involving rather large amounts of warming. In terms of how probable each of those is, there's a lot of debate, but in terms of actually making policy, you have to look at all possibilities and figure out possible actions you could take to limit the damage from climate change. Then you need to put price tags on each of these. With that kind of information, you can decide the policies you want to adopt and how to spend your money. I don't think that whole analysis has really been thoroughly done. The UNFCCC has focused on one policy—carbon cap-and-trade and emissions reductions. There's a whole host of others. Even if you're focused on limiting CO2, there are taxes, and there is the possibility that through technology the problem will solve itself without cap-and-trade or a carbon tax. On the adaptation and geoengineering side, there's a whole host of possibilities. These haven't been assessed. Instead we've been fighting this little war over science.

Should we wait to resolve all the uncertainty before taking action?
The probability of something bad happening is at least as high as the probability that there were weapons of mass destruction in Iraq. That turned out not to be true, but we ended up going in there anyway. So we have a history of taking action on bad things that have a low probability of happening.

Is it fair to say that the kind of open inquiry you are calling for isn't being done because scientists have been trying to convey a focused message to the public?
That's part of it. You heard that in the [hacked] e-mails: Let's simplify the story for the IPCC. But that's just not how science is. The scientists have gotten caught in these wars with the media and the skeptics. They spend so much energy trying to put them down, energy that isn't going into uncertainty analysis and considering competing views. I don't think the scientists have personal political agendas. I think it's more hubris and professional ego.

Do you agree that the Copenhagen meeting was a disaster?
Yes, it was.

So where does climate research go from here?
I personally don't support cap-and-trade. It makes economic sense but not political sense. You're just going to see all the loopholes and the offsets. I think you're going to see a massive redistribution of wealth to Wall Street, and we're not going to reduce the carbon dioxide in the atmosphere. We need a massive investment in technology. We do need to help the developing world that is most vulnerable now to the impacts of climate variability, not even the stuff that's related to carbon dioxide. There are a lot of things going on—floods, hurricanes, droughts, and whatever—that can't even be attributed to global warming right now. By reducing the vulnerability of the developing world to these extreme events, we'll have gone a long way to helping them adapt to the more serious things that might come about from global warming.

Do you think the IPCC is going to have a reduced role?
If they are going to continue to be relevant, they need to tighten up their act in terms of making the process more open and transparent. How do you actually get to be a lead author of the IPCC? I have no idea who actually makes those selections. Things like that. All the data sets need to be out there and available and documented, so we don't have these issues that we ran into with the hacked e-mails. The UNFCCC has become a big free-for-all. The G20, or some other group of nations, is where you're going see the action.

Do you subscribe to the argument that today's climate models are crude and need to be taken with a grain of salt?

No, I think the climate models are becoming quite sophisticated. We learn a lot from the simulations. But you have to keep in mind that these are scenario simulations. They're not really forecasts. They don't know what the volcano eruptions are going to be. They don't know what the exact solar cycles are going to be. There will be a whole host of forcing uncertainties in the 21st century that we don't know.

You've said that climatologists should listen more to bloggers. That's surprising to hear, coming from a scientist.

There are a lot of people with Ph.D.s in physics or chemistry who become interested in the climate change story, read the literature, and follow the blogs—and they're unconvinced by our arguments. There are statisticians, like McIntyre, who have gotten interested in the climate change issue. McIntyre does not have a Ph.D. He does not have a university appointment. But he's made an important contribution, starting with criticism of the hockey stick. There's a Russian biophysicist I communicate with who is not a climate researcher, but she has good ideas. She should be encouraged to pursue them. If the argument is good, wherever it comes from, we should look at it.

What about arguments on talk radio?
No, we debunk those once and then move on.

Is there a denial machine?
It's complicated. The denial thing is certainly not monolithic. The skeptics don't agree with each other at all. The scientific skeptics—[hurricane forecaster] Bill Gray and [MIT meteorologist] Dick Lindzen and [University of Alabama climatologist] Roy Spencer—criticize each other as much as we criticize them.

You wrote an article for climateaudit.org, a conservative Web site. Are people now calling you a denier?

No, they're calling me naive. I stepped off the reservation, clearly.

Are you taking a career risk?
A couple of people think so, but I'm senior enough and well-established enough that it doesn't matter. I also live in Georgia, which is a hotbed of skeptics. The things I'm saying play well in Georgia. They don't play very well with a lot of my colleagues in the climate field.

Does it bother you that *skeptic* has become a bad word?
It's an unfortunate word. We should all be skeptical of all science. The word *denier* has some unfortunate connotations also. I use "scientific skeptics" versus "political skeptics." A scientific skeptic is somebody who's doing work and looking at the arguments. A political skeptic is somebody who is getting the skepticism from talk radio.

Michael Mann is the director of Pennsylvania State University's Earth System Science Center. *Photography*

Ever since his "hockey stick" graph of rising temperatures figured prominently in Al Gore's An Inconvenient Truth, *Mann has been at the center of the climate wars. His e-mail messages were among those stolen and widely published last November.*

Let's talk about the hacked e-mails and the ensuing climategate scandal. What happened?
My understanding—and I only know what I've read from other accounts—is that hackers broke into the Climatic Research Unit of the University of East Anglia and stole thousands of e-mail messages, which they then proceeded to distribute on the Internet. They even tried to hack into a Web site that I help run, calledRealClimate.

by Imke Lass

Does anybody yet know where the attack came from?
No. There are many of us who would really like to know because obviously this is a serious criminal breach. And yet there's been very little discussion, unfortunately, about the crime.

Who might have done the hacking?
It appears to have been extremely well orchestrated, a very professional job. There also appears to have been a well-organized PR campaign that was all ready to go at the time these e-mails were released. And that campaign, involving all sorts of organizations that have lobbied against climate change legislation, has led some people to conclude that this is connected to a larger campaign by special interests to attack the science of climate change, to prevent policy action from being taken to deal with the problem.

Are you talking about the so-called denial machine?
These aren't my own inferences. I'm talking about what I've read on other sites. Interestingly enough, in the January 14, 2010, issue of *Nature*, there is a review of a book called *Climate Cover-Up*, by James Hoggan and Richard Littlemore, which details what I've just described to you. Back in 2006 there was a perfect storm of sorts. The IPCC had just come out with stronger conclusions. Al Gore's movie inspired people to get interested in climate change. We had some hot summers; we had some very destructive hurricane seasons. To say hurricane Katrina was an indication of climate change is no more correct than saying the current cold outbreak is evidence against climate change—I mean, that's weather—but it does influence people. A lot of things came together. There was a concerted effort by special interests who are opposed to policies to combat climate change to retrench and fight even harder in their campaign to discredit the science. There has been a lot more misinformation and, indeed, disinformation about climate change in the public discourse since then.

What about the e-mails themselves? Was it embarrassing having them brought to light?
Nobody likes having their personal e-mail exposed. We can all imagine, I think, what that would be like.

There's an investigation at Penn State, where you work, into your own role in this. How is that going?
Technically it's not an investigation. It's an inquiry to determine if there is a reason for an investigation. [*Editor's note: The inquiry subsequently reported that it had found no credible evidence that Mann had suppressed or falsified data*.]

Do you think you and your colleagues did anything wrong?
There's nothing in any of these e-mails that demonstrates any inappropriate behavior on my part. There are a few things that a certain colleague said that I wouldn't have said and I can't necessarily condone, although I can say that they were under a huge amount of pressure. They were attacked by FOIA [Freedom of Information Act] demands. A colleague of mine, Phil Jones, had as many as 40 FOIA demands—frivolous demands—made against him over a single weekend. Frankly, he showed some poor judgment, and there are things I said that I would phrase differently, obviously, if I were saying them in public. But there's nothing in any of these e-mails, despite the claims of those attacking us, that indicate any sort of conspiracy among climate change researchers to commit fraud, that indicate any destruction of data.

+

What about the references to "cleaning up" data? Does that amount to destruction?
No. In some cases there's been intentional misrepresentation of what people were talking about in the e-mail exchanges. *Nature* had an editorial [December 3, 2009] where they basically came out and said that the attackers of climate change had misrepresented two statements. One was about a "trick," which was simply a reference to a clever mathematical approach to a problem, the way scientists use the term *trick*: "Here's the trick to solving that problem," or "trick of the trade," and so on. And then conflating that with an unfortunately poorly worded phrase where Phil Jones refers to hiding a decline in temperatures. Much hay has been made of that. But these are internal discussions among scientists who understand the lingo and understand what it means and understand the context. And it's extremely easy for those looking to make mischief to take single words and phrases out of context.

Judith Curry has been an outspoken critic of your work and of a lot of climate researchers in general.
Did you ask Judith to turn over her e-mails from the past three years? Once she does that, then she's in a position to judge other scientists. Until she does that, she is not in a position to be talking about other scientists. Glass houses. Look, I'll just say this. I've received e-mails from Judith that she would not want to be made public.

She said that some data discussed in these e-mails concerned a temperature bump in the 1930s and 1940s, caused by a coincidence of Atlantic and Pacific decadal oscillations.
Yeah, I came up with the term: Atlantic Multidecadal Oscillation. I coined the term in an interview with Richard Kerr [a writer for Science] in 2000 over a paper with Tom Delworth of the Geophysical Fluid Dynamics Laboratory and the NOAA Laboratory in Princeton, where we actually were the ones to articulate the existence of this oscillation. And you know what? It was celebrated by contrarians. My work has been celebrated by climate skeptics. It's an interesting footnote.

Is Curry wrong in that regard?
I don't know exactly what she is referring to. She might be referring to a paper by Thompson et al. that appeared in *Nature*a couple of years ago about a spurious cooling in the 1940s that scientists couldn't quite understand.

She was referring to a rise and fall in temperatures in the 1930s and '40s that might have been caused by a coincidence of these oscillations in the Atlantic and Pacific, and another that could account for a lot of the warming in the 1990s. She was saying that it looked bad that you were trying to smooth out the bump in the '30s and '40s but not the one in the 1990s. Is that a valid critique?
The way you characterize it, it sounds like nonsense. I'm not sure how much familiarity she has, for example, with time-series smoothing. I've published a number of papers on this topic, and in fact, the approach that I take was used in the most recent IPCC report. I actually take a very objective approach to the problem of time-series smoothing. I'm not sure she understands the problem. It is very much the mainstream view in the climate research community that you cannot explain the warming of the past few decades without anthropogenic and human influences on climate.

If Phil Jones was being inundated by requests for data, why didn't he just post everything on the Web for all to see?

It is very much my practice and the practice of all the scientists I know, at least now, under the sort of criticisms that were made 10 years ago about data archiving policies, to make available every scrap of data that we use in our studies that we are legally permitted to make available. With the Climatic Research Unit's situation, what you have here is much [less] nefarious than it sounds. The Climatic Research Unit had legal agreements with certain countries that allowed them to use thermometer measurements, but they were legally bound not to distribute the data. The FOIA requests were demands for them to release those data, which they were legally bound not to release. The requests were disingenuous, and they were denied.

But all the rest of the data were released?
Yeah. The irony is that the data that they weren't releasing made no difference to the results.

The National Academy of Sciences supported the key point of your hockey stick calculation, which showed higher temperatures in the 20th century than in the previous thousand years, but others criticized you for not releasing the information behind it. Is all that data now in the public domain?
It is. And it was released as soon as we were allowed to do so. I don't produce any data myself. I just make use of other people's data. Often scientists in a purely collegial spirit will make available to you data that they haven't published yet. If you use it, you can't distribute it. Every single piece of data that we had the right to distribute was available at the time that we published the paper. Once we had permission to publish the smaller number of other records that we hadn't been able to make available at the time, those were out there.

By May 2000 all of the data were available. All of the claims that our data were not available at the time—by, for example, McIntyre, who's been leading these attacks—are entirely false.

Many scientists were dismayed by the climate talks in Copenhagen. What was your reaction?
There are people in the policy world who would like to see action taken much more quickly, and there are some objective, scientific arguments for that. If we can stabilize CO2 concentrations at 450 parts per million, it gives us probably at least 2 degrees of warming. Some people feel that any more than that and we'll really start to see the most threatening impacts of climate change. That requires essentially immediate action to slow down emissions and bring them to a peak, then start bringing them down fairly quickly over the next 50 years.

Were you disappointed at the lack of action?
I try to approach this from a scientific point of view. My understanding of the science does lead me, personally, to believe that certain policy options are better than others. But the policy in no way influences my science, and I think that's the way it should be.

Public opinion, at least in this country, has shifted toward the skeptical.
It has moved in that direction.

What should scientists do about that?
Right now, there's the largest disconnect that has ever existed between the confidence that we have scientifically and where the public is, at least in the United States. With each passing year, we've got more observations. We've got a better assessment of what's happening now in the perspective of what happened in the past, so we can better determine if there are climate trends that are unusual. We have more information about how the system is evolving in response to human impact. We also have supercomputers that are much more powerfu +

The models we run now produce El Niño events just like they occur in nature. The models are getting better. The science is getting more certain.

Even as the science becomes progressively more certain, the public discourse goes through these cycles. We've had the reverse of the perfect storm we had back in 2006. Some people say climate change became too closely associated with a partisan political figure and that polarized the debate. We've had a cold winter. We've got a bad economy. It's a bad time to be talking about major changes in our energy economy that some argue could be costly.

The biggest bludgeon the skeptics have is that there is uncertainty in the science. Should you and your colleagues be making more of an effort to quantify that uncertainty?
We've reached a point now in the interdisciplinary growth of our science where we've got climate scientists, who understand the physics of climate and how that translates to uncertainties, working hand in hand with economists who will run the projected impacts through a cost-benefit analysis. The way it plays out is that the small probability of extremely bad things happening incurs huge potential costs, and you want to hedge against those potential catastrophic costs. So when you take uncertainty into account, it actually leads to the decision that we should take action more quickly.

What is the worst-case scenario? Are we talking about the risk of our demise as a species?
That's what scares me, yeah. Now it appears that the antiscience side is in a much better position from a public relations point of view than the scientific community is. I see nothing to change that dynamic. The way our system works, it almost ensures that as an environmental threat grows, there is an institution in place that acts in a way to thwart the attempt by civilization to confront that threat. I fear that it isn't just a short-term thing. If that is our future, I worry. I have a 4-year-old daughter, and I care about the world that she grows up in.

How do you do research in an environment that is so politicized?
It's difficult. And needless to say, I'm not getting a lot of science done right now. Half my job involves defending myself against attacks.

Has the political polarization had a detrimental effect on progress in climate science?
It has. Here's the most basic example: Scientists like to communicate by e-mail. It's much more efficient. You can respond whenever you want. Scientists aren't going to be doing that as much anymore. When you do write an e-mail, you'll probably take twice as long because you want to make sure that every word can't be cherry-picked and distorted. You're second-guessing yourself at every stage and, sure, that slows everything down.

FROM THE MARCH 2010 ISSUE

The Doctor Who Drank Infectious Broth, Gave Himself an Ulcer, and Solved a Medical Mystery

The medical elite thought they knew what caused ulcers and stomach cancer. But they were wrong—and didn't want to hear otherwise.

By Pamela Weintraub | Thursday, April 08, 2010

RELATED TAGS: INFECTIOUS DISEASES

Barry Marshall, whose work with Helicobacter pylori bacteria led to a treatment for stomach ulcers.

Ian Regnard

For years an obscure doctor hailing from Australia's hardscrabble west coast watched in horror as ulcer patients fell so ill that many had their stomach removed or bled until they died. That physician, an internist named Barry Marshall, was tormented because he knew there was a simple treatment for ulcers, which at that time afflicted 10 percent of all adults. In 1981 Marshall began working with Robin Warren, the Royal Perth Hospital pathologist who, two years earlier, discovered the gut could be overrun by hardy, corkscrew-shaped bacteria called *Helicobacter pylori*. Biopsying ulcer patients and culturing the organisms in the lab, Marshall traced not just ulcers but also stomach cancer to this gut infection. The cure, he realized, was readily available: antibiotics. But mainstream gastroenterologists were dismissive, holding on to the old idea that ulcers were caused by stress.

Unable to make his case in studies with lab mice (because *H. pylori* affects only primates) and prohibited from experimenting on people, Marshall grew desperate. Finally he ran an experiment on the only human patient he could ethically recruit: himself. He took some *H. pylori* from the gut of an ailing patient, stirred it into a broth, and drank it. As the days passed, he developed gastritis, the precursor to an ulcer: He started vomiting, his breath began to stink, and he felt sick and exhausted. Back in the lab, he biopsied his own gut, culturing *H. pylori* and proving unequivocally that bacteria were the underlying cause of ulcers.

Marshall recently sat down with DISCOVER senior editor Pam Weintraub in a Chicago hotel, wearing blue jeans and drinking bottled water without a trace of *Helicobacter*. The man *The Star* once called "the guinea-pig doctor" can now talk about his work with the humor and passion of an outsider who has been vindicated. For their work on *H. pylori*, Marshall and Warren shared a 2005 Nobel Prize. Today the standard of care for an ulcer is treatment with an antibiotic. And stomach cancer—once one of the most common forms of malignancy —is almost gone from the Western world.

Having rid much of the globe of two dread diseases, Marshall is now turning his old enemy into an ally. As a clinical professor of microbiology at the University of Western Australia, he is working on flu vaccines delivered by brews of weakened *Helicobacter*. And in an age when many doctors dismiss unexplained conditions as "all in the head," Marshall's story serves as both an inspiration and an antidote to hubris in the face of the unknown.

You grew up far from big-city life. What was it like?
I was born in Kalgoorlie, a gold mining town about 400 miles east of Perth. My father was a fitter and turner, fixing steam engines and trains. My mother was a nurse. All the miners owed a lot of money and drank a lot of beer, so Mom said, "We've got to get out of here before we go the way of everybody else." In 1951 we headed for Rum Jungle, where a uranium boom was on, but halfway there we stopped in Kaniva, another boomtown, with a whaling station and high-paying jobs. Then my father started managing chicken factories in Perth. We never wanted for anything. It was like the TV show *Happy Days*.

What sparked your interest in science?
My mother had nursing books around. I had three brothers, and we always had electronics and gunpowder and explosions and welding. All I can say is that some things you get from your parents through osmosis. In high school I had Bs and Cs, not too many As, but I must have done well on that medical school test and I must have had some charisma in the interview, so I ended up in medicine. Being a general practitioner was all I aspired to. I was good with patients and very interested in why things happened. Eventually I developed a more mature approach: I realized that at least 50 percent of patients were undiagnosable.

You found yourself confronting unexplainable diseases?
In medical school it's quite possible to get taught that you can diagnose everybody and treat everything. But then you get out in the real world and find that for most patients walking through your door, you have no idea what's causing their symptoms. You could slice up that person into a trillion molecules and study every one and they'd all be completely normal. I was never satisfied with saying that by ruling out all these diseases, a person must have a fake disease, so I accepted the fact that lots of times I couldn't reach a fundamental diagnosis, and I kept an open mind.

Is that how you came to rethink the cause of ulcers?
Before the 20th century, the ulcer was not a respectable disease. Doctors would say, "You're under a lot of stress." Nineteenth-century Europe and America had all these crazy health spas and quack treatments. By the 1880s doctors had developed surgery for ulcers, in which they cut off the bottom of the stomach and reconnected the intestine. We're pretty certain now that by the start of the 20th century, 100 percent of mankind was infected with *Helicobacter pylori*, but you can go through your whole life and never have any symptoms.

What was the worst-case scenario for ulcer patients?
An ulcer with a hole in it, called a duodenal ulcer, is acutely painful due to stomach acid. When you eat a meal, the food washes the acid away temporarily. When the meal is digested, the acid comes back and covers the raw base of the ulcer, causing pain to start up again. These problems were so common that the Mayo Clinic was built on gastric surgery. After that surgery, half the people would feel better. But about 25 percent of these cured patients became so-called gastric cripples, lacking appetite and never regaining complete health.

With so much physical evidence of a real condition, why were ulcers routinely classified as psychosomatic?
Eventually doctors realized they could see the ulcers with X-ray machines, but, of course, those machines we

in big cites like New York and London—so doctors in those cities started identifying ulcers in urban businessmen who probably smoked a lot of cigarettes and had a high-pressure lifestyle. Later, scientists induced ulcers in rats by putting them in straitjackets and dropping them in ice water. Then they found they could protect the rats from these stress-based ulcers by giving them antacids. They made the connection between ulcers, stress, and acid without any proper double-blind studies, but it fit in with what everybody thought.

How did you come to challenge this prevailing theory?

I was in the third year of my internal medicine training, in 1981, and I had to take on a project. Robin Warren, the hospital pathologist, said he had been seeing these bacteria on biopsies of ulcer and stomach cancer patients for two years, and they were all identical.

What was distinctive about these infections?

The microorganisms all had an S-shaped or helical form, and the infections coated the stomach. Warren had found them in about 20 patients who had been sent to him because doctors thought they might have cancer. Instead of cancer, he had found these bacteria. So he gave me the list and said, "Why don't you look at their case records and see if they've got anything wrong with them." It turned out that one of them, a woman in her forties, had been my patient. She had come in feeling nauseated, with chronic stomach pain. We put her through the usual tests, but nothing showed up. So of course she got sent to a psychiatrist, who put her on an antidepressant. When I saw her on the list, I thought, "This is pretty interesting."

photography by Ian Regnard

Then another patient turned up, an old Russian guy who had severe pains. Doctors gave him a diagnosis of angina, pain that occurs when blood to the heart can't pass through a narrowed artery. It's rare, but you can theoretically get that in your gut, too. There was no treatment for an 80-year-old man in those days, so we put him on tetracycline and sent him home. He goes off, and two weeks later he comes back. He's got a spring in his step, he's practically doing somersaults into the consulting room. He's healed. Clearing out the infection had cured him. I had one more year to go, so I did the paperwork to set up a proper clinical trial with 100 patients to look for the bacteria causing the gut infection; that started in April of 1982.

But at first nothing was turning up, right?

Yes—not until patients 34 and 35, on Easter Tuesday, when I got this excited call from the microbiologist. So I go down there and he shows me two cultures, the grand slam, under the microscope. The lab techs had been throwing the cultures out after two days because with strep, on the first day we may see something, but by the second day it's covered with contamination and you might as well throw it in the bin. That was the mentality of the lab: Anything that didn't grow in two days didn't exist. But *Helicobacter* is slow-growing, we discovered. After that we let the cultures grow longer and found we had 13 patients with duodenal ulcer, and all of them had the bacteria.

When did you realize *H. pylori* caused stomach cancer, too?
We observed that everybody who got stomach cancer developed it on a background of gastritis, an irritation or inflammation of the stomach lining. Whenever we found a person without *Helicobacter*, we couldn't find gastritis, either. So as far as we knew, the only important cause of gastritis was *Helicobacter*. Therefore, it had to be the most important cause of stomach cancer as well.

How did you get the word out about your discovery?
I presented that work at the annual meeting of the Royal Australasian College of Physicians in Perth. That was my first experience of people being totally skeptical. To gastroenterologists, the concept of a germ causing ulcers was like saying that the Earth is flat. After that I realized my paper was going to have difficulty being accepted. You think, "It's science; it's got to be accepted." But it's not an absolute given. The idea was too weird.

Then you and Robin Warren wrote letters to *The Lancet*.
Robin's letter described the bacteria and the fact that they were quite common in people. My letter described the history of these bacteria over the past 100 years. We both knew that we were standing at the edge of a fantastic discovery. At the bottom of my letter I said the bacteria were candidates for the cause of ulcers and stomach cancer.

That letter must have provoked an uproar.
It didn't. In fact, our letters were so weird that they almost didn't get published. By then I was working at a hospital in Fremantle, biopsying every patient who came through the door. I was getting all these patients and couldn't keep tabs on them, so I tapped all the drug companies to request research funding for a computer. They all wrote back saying how difficult times were and they didn't have any research money. But they were making a billion dollars a year for the antacid drug Zantac and another billion for Tagamet. You could make a patient feel better by removing the acid. Treated, most patients didn't die from their ulcer and didn't need surgery, so it was worth $100 a month per patient, a hell of a lot of money in those days. In America in the 1980s, 2 to 4 percent of the population had Tagamet tablets in their pocket. There was no incentive to find a cure.

But one drug company did provide useful information, right?
I got an interesting letter from a company that made an ulcer product called Denel, which contained bismuth—much like Pepto-Bismol in the United States. The company had shown that it healed ulcers just as quickly as Tagamet, even though the acid remained. The weird thing was that if they treated 100 patients with this drug, 30 of them never got their ulcer back, whereas if you stopped Tagamet, 100 percent would get their ulcer back in the next 12 months. So the company said: "This must heal ulcers better than just removing the acid. It must do something to the underlying problem, whatever that is." They sent me their brochure with "before" and "after" photographs. On the "before" photograph they had *Helicobacter* in the picture, and in the "after" picture there was none. So I put their drug on *Helicobacter* and it killed them like you wouldn't believe. They helped me present at an international microbiology conference in Brussels.

The microbiologists in Brussels loved it, and by March of 1983 I was incredibly confident. During that year Robin and I wrote the full paper. But everything was rejected. Whenever we presented our stuff to gastroenterologists, we got the same campaign of negativism. I had this discovery that could undermine a $3 billion industry, not just the drugs but the entire field of endoscopy. Every gastroenterologist was doing 20 or 30 patients a week who might have ulcers, and 25 percent of them would. Because it was a recurring disease that you could never cure, the patients kept coming back. And here I was handing it on a platter to the infectious-disease guys.

Didn't infectious-disease researchers support you, at least?
They said: "This is important. This is great. We are going to be the new ulcer doctors." There were lots of people doing the microbiology part. But those papers were diluted by the hundreds of papers on ulcers and acid. It used to drive me crazy.

To move forward you needed solid experimental proof. What obstacles did you encounter?
We had been trying to infect animals to see if they would develop ulcers. It all failed; we could not infect pigs or mice or rats. Until we could do these experiments, we would be open to criticism. So I had a plan to do the experiments in humans. It was desperate: I saw people who were almost dying from bleeding ulcers, and I knew all they needed was some antibiotics, but they weren't my patients. So a patient would sit there bleeding away, taking the acid blockers, and the next morning the bed would be empty. I would ask, "Where did he go?" He's in the surgical ward; he's had his stomach removed.

What led up to your most famous and most dangerous experiment, testing your theory on yourself?
I had a patient with gastritis. I got the bacteria and cultured them, then worked out which antibiotics could kill his infection in the lab—in this case, bismuth plus metronidazole. I treated the patient and did an endoscopy to make sure his infection was gone. After that I swizzled the organisms around in a cloudy broth and drank it the next morning. My stomach gurgled, and after five days I started waking up in the morning saying, "Oh, I don't feel good," and I'd run in the bathroom and vomit. Once I got it off my stomach, I would be good enough to go to work, although I was feeling tired and not sleeping so well. After 10 days I had an endoscopy that showed the bacteria were everywhere. There was all this inflammation, and gastritis had developed. That's when I told my wife.

How did she react?
I should have recorded it, but the meaning was that I had to stop the experiment and take some antibiotics. She was paranoid that she would catch it and the kids would catch it and chaos—we'd all have ulcers and cancer. So I said, "Just give me till the weekend," and she said, "Fair enough."

Your personal experience convinced you that *Helicobacter* infection starts in childhood. Can you explain?
At first I thought it must have been a silent infection, but after I had it, I said, "No, it's actually an infection that causes vomiting." And when do you catch such infections? When you're toddling around, eating dirty things and playing with your dirty little brothers and sisters. The reason you didn't remember catching *Helicobacter* is that you caught it before you could talk.

You published a synthesis of this work in *The Medical Journal of Australia* in 1985. Then did people change their thinking?
No, it sat there as a hypothesis for another 10 years. Some patients heard about it, but gastroenterologists still would not treat them with antibiotics. Instead, they would focus on the possible complications of antibiotics. By 1985 I could cure just about everybody, and patients were coming to me in secret—for instance, airline pilots who didn't want to let anyone know that they had an ulcer.

So how did you finally convince the medical community?

I didn't understand it at the time, but Procter & Gamble [the maker of Pepto-Bismol] was the largest client of Hill & Knowlton, the public relations company. After I came to work in the States, publicity would come out. Stories had titles like "Guinea-Pig Doctor Experiments on Self and Cures Ulcer," and Reader's Digest and the National Enquirer covered it. Our credibility might have dropped a bit, but interest in our work built. Whenever someone said, "Oh, Dr. Marshall, it's not proven," I'd say: "Well, there's a lot at stake here. People are dying from peptic ulcers. We need to accelerate the process." And ultimately, the NIH and FDA did that. They fast-tracked a lot of this knowledge into the United States and said to the journals: "We can't wait for you guys to conduct these wonderful, perfect studies. We're going to move forward and get the news out." That happened quite quickly in the end. Between 1993 and 1996, the whole country changed color.

You have since devised tests for *H. pylori*. How do they work?

The first diagnostic test, done after a biopsy, detected *Helicobacter* that broke down urea to form ammonia. More recently I developed a breath test for *Helicobacter* based on the same principle. That test was bought by Kimberly-Clark, and they sell it all over the world. That one little discovery set me up for the rest of my career.

Is it possible to create a vaccine against *Helicobacter*?

After 20 years and a lot of hard work by companies spending millions, we have still been unable to make a vaccine. The reason is that once it's in you, *Helicobacter* has control of your immune system. Once I realized this, I said, well, if it's too difficult to make a vaccine against H. pylori, what about loading a vaccine against something else onto the *Helicobacter* and using it as a delivery system? So that is my vaccine project, and it is my life at the moment. I'm making a vaccine against influenza. We'll find a strain of *Helicobacter* that doesn't cause any symptoms. Then we'll take the influenza surface protein and clone that into *Helicobacter* and figure out how to put it in a little yogurt-type product. You just take one sip and three days later the whole surface of your stomach is covered with the modified *Helicobacter*. Over a few weeks, your immune system starts reacting against it and also sees the influenza proteins stuck on the surface, so it starts creating antibodies against influenza as well.

How would this be better than current flu vaccines?

Right now it takes a year to make 50 million doses of flu vaccine, so you only get vaccinated against last year's flu. Whereas we are building swine flu vaccine as we speak. We know the sequence of the swine flu virus. You can make the DNA. You can put it in *Helicobacter*—with a home brew kit, I can make 100,000 doses in my bathtub. Using the same method, a *Helicobacter* vaccine against malaria would be dirt cheap. You could make 100 million doses in the middle of Africa without a refrigerator. You could distribute it at the airport through something like a Coke machine.

Based on this experience, should we be taking a fresh look at other diseases that do not have well-understood causes?

Helicobacter made us realize that we can't confidently rule out infectious causes for most diseases that are still unexplained. By the 1980s, infectious disease was considered a has-been specialty, and experts were saying everyone with an infectious disease could be cured by antibiotics. But what about when your kids were 2 years old? Every week they'd come home with a different virus. You didn't know what the infections were. The kids had a fever for two days, they didn't sleep, they were irritable, and then it was over. Well, you think it is over. It might be gone, but it has put a scar on their immune system. And when they grow up, they've developed colitis

+

or Crohn's disease or maybe eczema. There are hundreds of diseases like this, and no one knows the cause. It might be a germ, just one you can't find.

How can we track down these mystery pathogens?

What we would like to do, hopefully with funding from NIH, is launch big, long-term programs. You would enter your baby into a trial the day he is born. We would have his genome decoded. We'd survey your microbiome [all the microorganisms in the body and their DNA] and maybe your husband's microbiome, and all that would go in a database. Then we would come along and take a feces culture from your baby each month. And if ever he got a fever, we would swab his cheek and save that. We would do 10,000 kids like this. Then, in 20 years' time, we would find that 30 of them developed colitis, and we would go back. If we could get all of that material out of the deep freeze and run it through the sequencing machine, we would find the answer. In the last 20 years, people have been so focused on linking disease with environmental factors like chemicals and pollution. But the environmental factor could be an infectious agent that you had in your body at some time in your life. Just because somebody ruled out an infectious cause in the 1980s or '90s doesn't mean this was correct. Technology has moved forward a long way.

Even now, though, isn't it hard for new ideas to be heard when medical journals are gatekeepers of the status quo?

It's true, but they have their ears pricked up now because every time a paper comes to them, they say: "Hang on a minute, I had better make sure that this is not a Barry Marshall paper. I don't want to have my name on that rejection letter he shows in his lectures." Now they might say, "It's so off-the-wall....Is it true?"

FROM THE JUNE 2010 ISSUE

Discover Interview: The Math Behind the Physics Behind the Universe

Shing-Tung Yau explains how he discovered the hidden dimensions of string theory.

By Pamela Weintraub | Tuesday, April 27, 2010

RELATED TAGS: MATH, STRING THEORY


photography by Shannon Taggart

Shing-Tung Yau is a force of nature. He is best known for conceiving the math behind string theory—which holds that, at the deepest level of reality, our universe is built out of 10-dimensional, subatomic vibrating strings. But Yau's genius runs much deeper and wider: He has also spawned the modern synergy between geometry and physics, championed unprecedented teamwork in mathematics, and helped foster an intellectual rebirth in China.

Despite growing up in grinding poverty on a Hong Kong farm, Yau made his way to the University of California at Berkeley, where he studied with Chinese geometer Shiing-Shen Chern and the master of nonlinear equations, Charles Morrey. Then at age 29 Yau proved the Calabi conjecture, which posits that six-dimensional spaces lie hidden beneath the reality we perceive. These unseen dimensions lend rigor to string theory by supplementing the four dimensions—three of space and one of time—described in Einstein's general relativity.

Since then Yau has held positions at the Institute for Advanced Study, Stanford University, and Harvard (where he currently chairs the math department), training two generations of grad students and embarking on far-flung collaborations that address topics ranging from the nature of dark matter to the formation of black holes. He has won the Fields Medal, a MacArthur Fellowship, and the Wolf Prize.

Through it all, Yau has remained bluntly outspoken. In China he has called for the resignation of academia's old guard so new talent can rise. In the United States he has critiqued what he sees as rampant errors in mathematical proofs by young academics. Yau has also strived to speak directly to the public; his book *The Shape of Inner Space*, coauthored with Steve Nadis, is scheduled for publication this fall. He reflected on his life and work with DISCOVER senior editor Pamela Weintraub at his Harvard office over four days in February.

You've described your father as an enormous intellectual influence on you. Can you tell me about him?

He went to Japan to study economics, but he came back to help the Chinese defend themselves before the Japanese invaded in 1937. By the end of the war he was distributing food and clothes to the poor for the U.N. After the revolution in 1949, he worried about getting in trouble with the Communists, so he brought the whole family to Hong Kong. We were very poor—at first we were almost starving—but my father had a large group students constantly at home to talk about philosophy and literature. I was 10, 11, 12 years old, and I grew accustomed to abstract reasoning. My father made us memorize long essays and poems. At the time I didn't understand what they meant, but I remembered them and later made use of it.

Did part of you ever rebel?
I read most of the Kung Fu novels in secret. I quit school for more than half a year. I'd wake up and say I was going, but I'd spend the whole day exploring the mountains and then come back—but I did the homework that my father assigned to me at home.

I heard you led a gang at one point.
I had a group of friends under me. I'd go around, and sometimes we ended up in fistfights with some other groups. So?

How did you go from that rough-and-tumble young man to the focused person you are now?
In the early 1960s my father was chairman of the department of literature and philosophy at Hong Kong College. The college president wanted to make a deal with the Taiwanese government to send in spies. My father refused to go along and resigned. That created a big money problem because he had eight children by then. My father had to run around among different, distant colleges to support the family. Back in China he'd lent a friend some money, and after the Communists took over, the friend moved to Macau, a city near Hong Kong, and ran his own schools. So he told my father, "I cannot return your money, but your daughter can come to my school, and I'll give her free room and board and free tuition." So my older sister went to Macau to study and got some flu, some funny disease, we never knew exactly what. She came back and she was treated, but she died in 1962. Then my elder brother got a brain disease; at the time we didn't know what it was. My father had all kinds of burdens on his shoulders and then he got a disease, which I believe was cancer, but we didn't know much in those days. My mother was running around trying to get funding to help my father. Finally we raised some money, but it was too late. He died after two months in the hospital in 1963, in the middle of my studies in the ninth grade. We could no longer afford our apartment, so we were kicked out. That's when I realized I would have to make decisions for myself.

What did you do then?
After a while the government leased us some land, and we built a small house thanks to money from friends, but it was in a village far from school. The other kids looked down on us for being poor, and I had to ask the school president to allow me to pay tuition at the end of the year, when my government fellowship came through. It was humiliating. But I studied hard and did very well, especially in math. Then a former student of my father started a primary school in a town closer to school. He said I could help teach math and stay there at night. I had to take care of myself, I had to wash things and all of that, but I learned how to survive.

What happened once you made your way to college?
I had fallen in love with math early on, but at the Chinese University of Hong Kong I realized that mathematics was built on standard actions and logic. Soon I had arranged to take tests for the required math courses without actually attending while sitting in on more advanced classes, and no one seemed to mind. In my second year, Stephen Salaff, a young mathematician from U.C. Berkeley, came to teach in Hong Kong. He liked to talk to the students in the American way: He gave lectures and then he asked students questions. In many cases it turned out I could help him more than he helped me, because there were problems he couldn't solve during class.

Salaff suggested I apply to graduate school early. I was admitted to Berkeley and even got a fellowship. I borrowed some money from friends and flew to San Francisco in September 1969.

What did you think of California when you arrived?
The first thing that impressed me was the air. In Hong Kong it's humid, hot, but in California it was cool and clear. I thought it was like heaven. A friend of Salaff's came to the airport to pick me up and took me to the YMCA, where I shared a big room with four or five people. I noticed that everybody was watching baseball on TV. We didn't have a TV at home. My neighbor who was sleeping there was a huge black man. He was talking in a language I had never heard before. He said, "Man, where the hell you come from?" It was fun, but I had to look for an apartment. I was walking around the street when I met another Chinese student from Hong Kong and we decided to share, but we couldn't afford a place. We looked around and found another Chinese student, from Taiwan, so there's three of us and it's still not enough. Then we found an Alaskan also studying math, also on the street. So four of us went in together and the rent for each was $60 a month. My fellowship gave me $300 a month, and I sent half of it home.

What about your math studies?
There were many holes in my knowledge so I'd wake up early and start class at 8 a.m. I took three classes for credit, and the rest I audited. I brought my own lunch so even at lunchtime I was in class. I was especially excited about topology because I thought it could help reveal the structure of space. Einstein used geometry in his equation to give us the local picture: how space curved around our solar system or a galaxy. But the Einstein equation didn't give the overall picture, the global structure of the whole universe. That's where topology came in.

What is topology? Is it like geometry?
Geometry is specific and topology is general. Topologists study larger patterns and categories of shapes. For example, in geometry, a cube and a sphere are distinct. But in topology they are the same because you can deform one into the other without cutting through the surface. The torus, a sphere with a hole in the middle, is a different form. It is clearly distinct from the sphere because you cannot deform a torus into a sphere no matter how you twist it.

Does that mean geometry and topology are really two perspectives on the same thing?
Yes. It is like Chinese literature. A poem might describe a farewell between lovers. But in the language of the poem, instead of a man and woman, there is a willow tree, where the leaves are soft and hanging down. The way the branch is hanging down is like the feeling of the man and the woman wanting to be together. Geometry gives us a structure of that willow tree that is solid and extensive. Topology describes the overall shape of the tree without the details—but without the tree to start with, we would have nothing.

It has always amazed me to observe how different groups of people look at the same subject. My friends in physics look at space-time purely from the perspective of real physics, yet the general theory of relativity describes space-time in terms of geometry, because that's how Einstein looked at the problem.

When you looked at the world through the lens of geometry and topology, what did you learn?
That nonlinear equations were fundamental because in nature, curves abound. Climate isn't linear. If the wind blows stronger that way, it may cause more trouble over there; it may even depend on the geometry of the earth. Usually you see the stock market described by linear equations and straight lines, but that is not really corre


photography by Shannon Taggart

The stock market fluctuates up and down in a nonlinear way. The Einstein equation described the curvature of the universe, and it was nonlinear. I ended up learning nonlinear equations from a master, although I didn't know he was a master at the time. His name was Charles Morrey, and he was a classical gentleman. He always dressed in suits in class. He was a very nice man. Even if I was the only one there, he would lecture to me, just as if he were lecturing to the whole class.

Wait—you were sometimes the only one in his class?
Why should people care about ancient days? Morrey didn't use modern notations. His book was hard to read. Kent State had just happened. The students and the faculty were all on strike, but Morrey still gave lectures. Soon everyone had dropped the class but me.

What happened next in your mathematical explorations?
It was Christmas break and I couldn't go home, so I spent my time at the library reading all the journals and looking at rare books. That was the first time I met my wife, although only much later were we formally introduced. Through all this reading about topology I came across a theorem that talked about loops where curvature is everywhere negative—where the curve goes in like a saddle. The theorem says that when we have two such loops with vertices at the same point, they can't deform into each other by bending or twisting unless they are equal to or multiples of each other. I came up with a related theorem: If the curvature is either negative or zero and if the loops conform, then there must be a lower-dimensional surface—specifically a torus—sitting somewhere inside.

How can a lower dimension sit inside a higher one?
Imagine attaching a rubber band to the handle of a coffee cup. The cup has three dimensions, but the rubber band, which is just a curved line, effectively has only one.

Why should anyone other than a mathematician care about a torus or a string hidden within higher dimensions?
Because topology can affect and constrain geometry in the physical world. If water flows around a sphere, for example, there must be two points where the water is totally still. On a planet covered with an ocean, the water can't all flow in the same direction, say east to west, everywhere, without hitting a snag. In the case of another topology, the torus, water can flow around and around and there's no point at which the flow stops because the hole eliminates the impasse. For each fixed topology, the geometry follows different laws.

In other words, you realized that topology sets the basic rules for geometry, which in turn affects the world around us. But then you went further, asking whether the underlying structure of space might explain the laws of physics. How so?
I started to look into complex manifolds. A manifold is just a space, with each point immediately around you

looking like Euclidean space—the familiar kind of space that we see around us. Imagine the earth is covered with a checkerboard or a grid, like latitude and longitude. This is the kind of coordinate system that Descartes introduced to geometry in the 17th century. At each point on the grid the space appears flat and finite, but it's actually curved, a sphere. Instead of being measured with real numbers, though, we measure complex manifolds with complex numbers, in which one of the coordinates includes a real number multiplied by the square root of negative 1—an imaginary number that we call i. [Since the product of two negative numbers is positive, ordinary math suggests the square root of negative 1 cannot exist—hence the moniker "imaginary."]

How can complex manifolds and complex numbers help us understand the structure of space?
Space is not necessarily something you see in day-to-day life. You can define geometry locally, but globally you cannot visualize the big picture, you can only imagine it and represent it through coordinates. We draw lines of latitude and longitude in a coordinate system for the continents. But that system doesn't work well at the north or south poles, where all the lines converge. In order to get a more complete picture in those regions, we need another, more localized coordinate system for more detail. In the end, we need several such coordinate systems patched together to get a detailed picture of the entire globe.

More generally, in describing any space, we are not restricted to the three dimensions we experience in our lives. Mathematically, we can suggest any number of dimensions: two, three, four, five, ten, just by drawing additional coordinates on a grid. In complex space, every number in a coordinate system describes not just one dimension but two. Most important, complex numbers make it simpler to move from one coordinate system to another, a necessary step when working in the higher dimensions necessary for string theory.

You are best known for your work on the Calabi conjecture, which at the time was a major unsolved problem in higher-dimensional mathematics. What attracted you to it?
I was drawn to important problems that gave insight into geometry and space-time. Sometimes solving a problem creates a new kind of thinking, sometimes the math itself is beautiful. The problem I went with, the Calabi conjecture, is a very elegant statement about the curvature of complex manifolds.

What does "curvature" mean in this context, since you aren't talking about the kind of curves we normally experience?
Curvature is second-order information—for instance, suppose I am driving a car around a curved freeway. The car's velocity will change as you go, so you can measure the curve in terms of changes in velocity along that one-dimensional line. Then there is Gauss curvature, which gives you the curvature of a two-dimensional surface by multiplying the largest and smallest curvature of the family of all curves tangential to the surface at a given point. For higher-dimensional space, such as the three-dimensional space around us, we calculate the curvature of all the two-dimensional surfaces passing through the point where curvature is in question. Finally there is Ricci curvature, which we measure by averaging the curvature of all two-dimensional surfaces tangential to each other along a common direction. In essence, Ricci curvature is an average of part of the total curvature of a space. It is an abstract geometric concept, but it is fundamental.

Why is Ricci curvature fundamental?
In physics, Ricci curvature is analogous to matter. Space with zero Ricci curvature is space without matter—a vacuum.

And how does all this relate to the Calabi conjecture?
Calabi said that certain topological conditions call for the existence of nonflat, closed, complex spaces without Ricci curvature anywhere. Such spaces would enjoy many beautiful properties. You might find the sub-dimensional loops or the torus I described in that very first paper I wrote—or you might find intersecting branes [short for "membrane," another topological shape]. I was 100 percent sure that the spaces Calabi called for could not exist. No mathematician or physicist had ever found an example of one, and most geometers considered them too good to be true.

So what did you do next?
I spent a lot of time thinking about how to disprove Calabi. By 1973 I was teaching at SUNY–Stony Brook and planning to move to Stanford. That May I put my belongings into this little Volkswagen and drove across the country on Highway 80. I thought America was a country where everyone traveled around, but to my amazement, a lot of the people I met told me they had never driven more than 10 miles from their town. I crossed the Rocky Mountains. The car broke down at one point. By the time I was at Stanford for a few months, I thought I had finally proven Calabi wrong.

Disproving the Calabi conjecture would have been a major achievement; how did you announce it?
In August there was a big conference at Stanford with the top geometers in the world, including Calabi. I talked to Calabi and told him my idea. He said, "That sounds great. Why don't you give a discussion about it to me?" It was scheduled for 7 p.m. Calabi brought a few colleagues from the University of Pennsylvania, and then a few others heard about it, and a few others. There was a little crowd. I talked for about an hour, and Calabi was excited. "I've been waiting for this for a long time, and I hope it's right," he said. All the other people said, "Great, finally we can stop the wishful thinking that Calabi is true." Then Calabi wrote to me in October. He said, "I'm trying to reconstruct your argument, and I'm having some difficulty. Could you explain the detail?" I started to reconstruct it and I found a problem too. I got totally embarrassed. I did not respond to Calabi at that moment and instead tried extremely hard to patch up the proof. I couldn't, so I looked around to find other examples where Calabi was wrong. I didn't sleep for two weeks. But every time I found an example that was close, the proof fell apart at the last minute. Finally I said, gee, this cannot be such a delicate matter. Now I had much deeper insight into the issue and felt there must be some truth to the whole thing. I determined that it had to be right.

So after all that work trying to prove that Calabi's conjecture was wrong, you decided it was correct after all?
I began developing the tools to understand it, and by 1975, only one part of the proof was left. That year my wife got a job in Los Angeles. I moved to UCLA. All in a short time, we got married, bought a car, bought a house in the Valley, and had to look for furniture. My mother came from Hong Kong for the wedding, and then her parents came—they all stayed under one roof and got into fights; it was complicated and crazy. I was fed up, so I locked myself in the study and thought about Calabi instead of the family problems, and I solved the whole thing. I went over the proof three times in detail, and I went to see Calabi in Pennsylvania. On a snowy Christmas Day, he came with me to visit mathematician Louis Nirenberg at New York University. We spent all day Christmas going over it, and I spent the next month writing up the proof for publication.

The implications were enormous. You were instantly famous.
It solved some major problems in algebraic geometry—about a dozen of them. A lot of people offered me jobs

Some of the higher-dimensional spaces now called Calabi-Yau spaces proved fundamental to string theory. What is the connection?

When Einstein published his general theory of relativity in 1915, there was an immediate urge to unify the force of gravity with the other forces known at the time, with electricity and magnetism. Mathematicians thought they could do this with five dimensions, four of space and one of time. But then physicists found new particles and needed extra dimensions for the strong force and the weak force. When they worked it all out, they determined they could explain the universe with something they called string theory, which replaces the pointlike particles in particle physics with tiny, elongated vibrating strings. To be consistent with quantum theory, the strings needed 10 dimensions in which to vibrate: three of space, one of time, and six dimensions of "compact space." Dimensions in compact space are so small you can't detect them through any conceivable experiment. They amount to pure structure. It so happens that Calabi-Yau spaces with six dimensions also have specific topological traits corresponding to the requirements of string theory. If these spaces truly modeled the six-dimensional space called for in string theory, they would help us deduce the geometry and, by extension, the physical laws of the universe.

Some cosmology theories imply the existence of other universes. Could each Calabi-Yau space describe a different set of laws in each of those universes?

Yes, each isolated universe can be modeled by a different Calabi-Yau space. But some of my colleagues have also studied a beautiful concept called mirror symmetry, in which each space has a mirror image with the same quantum field theory and the same physics.

How many Calabi-Yau spaces are there?

Using a computer program, Philip Candelas at the University of Texas at Austin found up to 10,000 Calabi-Yau spaces, with almost half of them mirror partners of each other. Each member of a pair is topologically distinct but still conforms to the other algebraically and gives rise to the same forces, the same particles, the same rules. The resulting geometric structure can be used to determine physical quantities associated with each space, like particle mass.

String theory is often described as a mathematically elegant way to explain all of physics. But how can we know that it describes the real universe?

We cannot know for sure, but the mathematics inspired by string theory solves some old, longtime questions. That part is rigorous and its truth cannot be challenged. If the structure of the math is deep, it will solve something in nature one way or another; it is difficult to imagine that such deep structure corresponds to nothing. Everything fundamental in math has ultimately had a meaning in the physical world. If these spaces modeled the six-dimensional space called for in string theory, they would help us deduce the geometry and the physical laws of the universe.

You've long promoted mathematics in China. How have academic conditions changed there over the years?

I first went back in 1979, right after China opened up to outsiders. People were poor. Times were difficult. It was bedlam. I saw lots of people who were uneducated, and I felt I needed to help. By 1985 I'd taught about 15 Chinese grad students accepted to programs in the States. At first it was my adviser and mentor, Shiing-Shen Chern, who went to China and founded a mathematical institute there. I didn't want to interfere with his work, but he was getting old and I started to go visit more often. In 1994 I was asked to give a speech. I said it's great

+

that China has an open policy; now we must start moving forward step by step, training young people to establish an intellectual base.

Eventually you founded four math institutes in China. How did that happen?
I met with Jiang Zemin, the future president, who wanted me to help build up math in China. After that, with the help of a donor, I built the Institute of Mathematical Sciences at the Chinese University of Hong Kong followed by three more institutes on the mainland—but China has always been run in a collaborative way, and other universities began demanding part of the funds. Still, the institutes have been able to carve out some independence, and today I go to China five or six times a year.

In the past decade, you've been critical of science and math in China. Why?
The university system is beset by academic politics, and it's difficult for young people to move ahead. When China opened up, the people running things were in their fifties and sixties. The same people are still running things. Most do not follow modern developments because of their age. There are some brilliant young people, but it is a struggle for them to be recognized. Often that happens in China only after they are recognized by the outside world. I said, "Give some freedom to the young guys," and people got upset.

You've commented that at the highest levels of accomplishment, Chinese mathematicians have far to go, and that the best of them have left the country. What are the prospects for math and science in China today?
The economy has been getting better and the government wants to invest more in science, so in the long run, I think the future is bright. Many more Chinese graduate students who come to study in the United States will be willing to return to China.

How does China's relationship with the United States come into play?
I see a constructive relationship for academia. The U.S. gets human resources in the form of bright, young Chinese kids. The students learn well here, because the U.S. provides them with the freedom to research in their own way, and some of them will bring their knowledge back to China. But my goal is to train many more young mathematicians within China by providing an environment that allows them to focus on research and be recognized for their work.

You have criticized the academic system in the United States as well.
Young people are under too much pressure here. As a result, some of the proofs they publish are factually wrong. Before I published my proof of the Calabi conjecture, I checked it three times. Many young mathematicians don't do that.

Most people don't realize how political math can be: In 2006 *The New Yorker* accused you of taking credit from the Russian mathematician Grigory Perelman after he proved the famed Poincaré conjecture. What happened there?
In a process as intricate and daunting as proving the Poincaré conjecture, it is understandable that Perelman released his manuscript with several key steps merely sketched or outlined. One of my students tried to fill in some of the details, and I supported that. I also said that my friend Richard Hamilton, a geometer at Columbia University, laid much of the groundwork that Perelman ultimately relied on to construct his proof. For these things *The New Yorker* tried to accuse me of stealing credit, but that is ridiculous. What I think of as the Hamilton-Perelman proof of the Poincaré conjecture is a great triumph for mathematics, and I fully support

award of the Fields Medal to Perelman. Hamilton deserved the Fields Medal too, but he was ineligible because of the age restriction [you must be under 40]. To suggest that my position has ever been any different is completely untrue.

Physicists often talk about the beauty of math. What does that mean to you?
The first time I saw my wife, I thought she was charming—more than charming, shocking to me. I had great motivation to know her more. When I look at the Calabi conjecture, it shocks me too. It's an elegant, simple construct and explains a great deal. It's exciting when you go deeper and deeper into a complicated structure that you can spend most of a lifetime working on. It was shocking when it showed up in physics, and it's beautiful whether it's true or not.

FROM THE BRAIN FALL 2010

The Love Neuroscientist: Q&A with Stephanie Ortique

Believe it or not, says psychologist Stephanie Ortigue, lust makes heavy intellectual demands involving complex thought.

By Eliza Strickland | Sunday, August 01, 2010

RELATED TAGS: MEMORY, EMOTIONS, & DECISIONS

Love is celebrated as a many-splendored thing, while lust is commonly regarded as downright primitive. Leave it to a Frenchwoman to discover that sexual desire is actually quite brainy. Stephanie Ortigue, an assistant professor of psychology at Syracuse University, uses brain scans to examine the divine madness of love and the blinding imperative of lust. Her goal: illuminating how these two forms of attraction work by mapping out which brain regions are active when we experience them. Her findings counter the assumption that desire is a simple animal urge motivated primarily by biochemistry and evolutionary directives.

Ben Gest

Working with her frequent collaborator, psychiatrist Francesco Bianchi-Demicheli of Geneva University Hospital in Switzerland, Ortigue has found that lust involves complicated cognitive processing. Love, too, is not quite what we thought. Both romance and desire, she says, may be expressions of a “top-down” process in which intellect rules over instinct, not the other way around. Love may even make you smarter, by helping your brain process information more quickly.

Why do you study the neuroscience of love and sex?
I’ve always been interested in the big questions of science, and love is one of the biggest questions in the world. Everyone feels it, knows what it is, but we can’t really define it. I like challenges, and I like to bring some rationality to things that seem irrational. Also, I’ve always been interested in the unconscious and consciousness and how the two interact in our daily life. We’ve found that a lot of unconscious processes are involved in love and desire.

What did you expect to find, and what has surprised you?
We all know that love and sex activate the limbic system, the emotional center of the brain. But I wondered if we could find more beyond that. Our results suggest that love and sex are not just animal processes; they are much more sophisticated and intellectual than we thought. In brain scans of people feeling sexual desire, we

find that visual areas and emotional areas were activated. What was surprising was the activation we saw in another brain region, one involved in complex cognitive processes.

How do you study the way people respond to desire?
We put pictures of good-looking people on a computer and asked participants to press a button every time they were attracted by a picture. We recorded their reaction times and found that responses were much faster when the participant was not attracted to someone. It's very easy to say, "Oh, no, he doesn't turn me on." But it took much longer for people to determine if they were attracted to someone, if they were feeling desire.

We analyzed the subjects' brain activity with 128-electrode, high-density EEG [electroencephalography] and compared their brain activity while they were feeling desire with activity when they were thinking, "No, not for me." When the subjects had no feeling of desire, we saw activity in an area involved in body recognition called the extrastriate body area, indicating, as you might expect, that they were evaluating the body they saw in the picture. But when they were feeling desire, we saw activation not only in the extrastriate body area but in a brain region called the temporo-parietal junction, which is known to be very important for the understanding of the self and one's own body image. This suggests that sexual desire isn't just a matter of evaluating a body. The brain is also doing some more surprising cognitive work.

With EEG, we know not only where desire occurs in the brain but when it activates each region. And we found this interesting dynamic: First we found activation in the visual area, and then following that—very fast, so it's still unconscious—we found lots of activity in this region [the temporo-parietal junction] that's involved in body image, and then back to the visual.

Why do you think we are able to find someone unattractive more quickly than we're able to judge them desirable?
It's as if you have an unconscious checklist in your mind: Does this guy fit my checklist or not? If there is one point that doesn't match, the guy is rejected. But if he passes the first point, then you have to check the next one and the next one. The thing that's fantastic about the desiring mind is that it all happens so quickly. Within 200 milliseconds our brain knows whether we desire someone—before we know it consciously!

If the temporo-parietal junction is involved in our own body image and sense of self, why does it engage when evaluating other people?
Ah, that is a very interesting question. We believe everything that happens to "self" is stored and processed in this temporo-parietal junction because it is important for integrating information and abstract concepts. So all the experiences you've had with desire, including positive experiences, are stored somewhere there—not just in the hippocampus [the primary memory-storing area of the brain]. When you meet a new person, your past experiences influence your evaluation of the person in the present moment.

You have also looked at the cognitive process of love. What did you find?
Again we were interested in how the unconscious influences behavior. We presented each participant with the name of his or her beloved on a monitor, subliminally [faster than the threshold of awareness], and contrasted that with the name of a friend and the name of a stranger.

Then we asked the participants to do a demanding cognitive task that required focused attention. Love is supposed to activate the dopamine system, which is involved in reward and pleasure but also plays a role in cognition and movement. Our hypothesis was that if love activates the dopamine system, it should boost functions related to that system, like cognition and motor functions. So we should see a faster reaction time.

We found a huge and significant effect when we presented the name of the beloved: The participants were much faster at the cognitive tasks that we were asking them to do, but only when we asked them to do challenging tasks. When we asked them to do less demanding tasks, we didn't see the same effect. We believe that passionate love activates a specific brain network that helps people make faster cognitive connections and mental associations. It isn't just speeding up their motor skills.

Do the patterns of brain activation associated with love overlap with those for lust?
We see two different networks for love and desire, but we're still trying to understand how they differ. They have common areas in the parietal lobe and the temporo-parietal junction. The desire network is more complex, more distributed than the love network. It's the opposite of phrenology: There's not just one part of the brain that does it all.

Are there practical applications for this research?
Yes, absolutely. If love and desire involve regions of the brain that govern the sense of self, then by understanding self-image we can not only help people who have body-image disorders, such as anorexia, but also help people who have desire and sex disorders. There is a famous saying in French, "Love yourself before you love others." It's a cliché, but maybe there is some truth to it.

FROM THE JULY-AUGUST 2010 ISSUE

Discover Interview: Alarming Tales of International Hacking from a Cyber-Terrorism Czar

Spies and hackers know only too well about the security loopholes that riddle the Internet—and maybe even the guts of our computers. Former presidential advisor Richard Clarke has ideas for how we can prepare for the new world of virtual combat.

By Robert Keating | Monday, November 08, 2010

RELATED TAGS: WEAPONS & SECURITY, COMPUTERS


Nathaniel Welch

On a September night in 2007, a swarm of Israeli jets swooped across Syrian airspace and destroyed a nuclear facility under construction. Despite Syria's sophisticated radar, their approach went unnoticed. The Israelis had hacked the Syrian equipment so all it showed was vast, empty sky. It is technology that cuts all ways: In the United States, hackers have breached the Pentagon, while spies from China have gained access to 1,300 computers in embassies around the globe. Richard A. Clarke, a counterterrorism czar to three administrations and the first special adviser to the president on cyber security, calls the Internet a "cyber battlefield." In his recent book, *Cyber War*, he discusses the vulnerability of the electrical grid, banking systems, air-travel networks, and national defense. Clarke recently visited the DISCOVER offices to discuss this emerging type of warfare.

You say the threat of cyber war begins with computer manufacturing. How so?

Take any piece of computer hardware—your laptop, your desktop, a router in the network. It has probably been assembled in one country, but the components have probably been made in two dozen: Taiwan, India, China, the United States, Germany. And the software has probably been written by thousands of people in many countries. You can't have high security when there are that many people involved. It's so easy to slip a trap door into 50 million lines of code for a piece of software. It's so easy to have a microscopic element on a motherboard that allows people to get in without authorization.

How could this sort of invasion happen?

In cyber war or cyber espionage, the person who's doing it can achieve access in dozens of different ways. Once they are in your computer or your local area network, they can see everything that goes on, they can copy information and exfiltrate that information, they can issue commands. If they've accessed a network that's controlling something, such as an electrical power grid or a railroad system, they can cause things to happen not in cyberspace but in physical space. They can control a rail switch or a valve on a pipeline.

How are we responding to the threat?
Last October the United States created a unit just like Strategic Command or Central Command; this one's called Cyber Command. Under Cyber Command is a Navy unit called the 10th Fleet that has no ships and an Air Force unit, the 24th Air Force, that has no planes. These units are designed to fight both offensively and defensively in cyberspace.

Has the United States ever experienced a serious case of cyber espionage?
The United States and several of its allies are building a new, fifth-generation fighter plane, the F-35 Lightning II, cutting-edge technology. There's good reason to believe that a foreign government, probably China, hacked into the manufacturing company for the aircraft and downloaded all the plans. So for this plane that hasn't even flown yet, a potential enemy knows its strengths and weaknesses. The really scary part is, if they got in, do you think they just copied information? Or do you think perhaps they inserted something in the software? Imagine the future where a U.S. F-35 is flying into combat and another nation sends up a much less capable airplane, but that other airplane can send out a signal that opens up a trapdoor in the software that's running the F-35 and causes it to crash. Airplanes these days, whether it's the F-35 or the 787, they're all software. The plane is just one big computer network with all sorts of things being run by software applications.

What do we need to do to keep the country secure from digital attack?
The United States is pretty good at offense; the government can probably hack its way into most anything. But we don't have a good defense. Right now the U.S. government is defending only itself, and that's largely the military defending the military. The Obama administration's attitude seems to be that if you're a bank or a railroad or a pipeline company or a power company, you should defend yourself. Imagine in the 1960s if our government had said to U.S. Steel in Pittsburgh or General Motors in Detroit, "The Soviet Union has a lot of bombers and those bombers could reach Pittsburgh or Detroit, so you, private company GM, private company U.S. Steel, should go out and buy some air-defense missiles."

What are the private companies saying in response?
They want it both ways. They want to minimize government involvement; they certainly don't want the government telling them how to structure their information technology systems. But at the same time, when you tell them the government of China could be hacking into their company, they say, "Well, why isn't the federal government stopping that? I pay my taxes." In the end, there's going to have to be a federal role larger than there is now. The fact that we have virtually no defense right now, that's largely a matter of policy—not so much of technology—and it would seem to be a rather obvious wrong choice, I think.

It sounds like we're the big, tough boxer with a glass jaw.
The line that I like to use is "People who live in glass houses shouldn't throw attack code." We should be taking the lead in arms control.

The fight against cyber attacks is a form of arms control?
I think if you do limits on cyber war, that's arms control. I worked in arms control for over 20 years. I did biological, nuclear, and conventional arms control. I know how hard it is. I negotiated a lot of agreements, and cyber war would be very difficult to negotiate. But some of those arms control agreements may actually have

stopped nuclear war. So let's not throw up our hands and say, "We can't do it in cyberspace with cyber war." Instead, let's get the arms control experts and the cyber experts together and see what we can do to reduce the chances of a damaging cyber war.

What is the biggest threat: national governments, terror groups, or individual hackers?
Individual hackers can make a lot of trouble, but they can't bring down a power grid. They can't do the really destabilizing infrastructure attacks that we're worrying about. Criminal gangs are getting better at it, and we're seeing cyber criminal gangs doing things that in the past only nations could do. So that is a worry. But for the most part our concern is cyber war directed nation to nation, because in addition to having lots of technology at your fingertips, nation-states have intelligence agencies. And intelligence agencies can provide the collateral information to figure out how to do an attack. Sometimes you need physical involvement, social engineering, information gathering before you do an attack.

What will it take for us to acknowledge the true magnitude of the threat?
When Russia cyber-attacked Estonia in 2007 and then a year later attacked Georgia, people said, "That's the wake-up call." When the Chinese attacks on Google occurred last year, people said, "Oh, that's the wake-up call." I think people would have to know that some great discomfort or some great violence had occurred because of deliberate malicious activity in a network.

FROM THE JULY-AUGUST 2010 ISSUE

Discover Interview: The Gene Doctor Will See You Soon

First he made a machine that can read DNA at lightning speed. Now Leroy Hood wants to reach into the genome to revolutionize medicine.

By Pamela Weintraub | Tuesday, November 16, 2010

RELATED TAGS: GENETIC ENGINEERING

José Mandojana

In 1985 Leroy Hood was one of the high-profile molecular biologists called to a power summit in Santa Cruz, California. The goal of the meeting was to determine whether an institute should be established there to sequence the entire human genome—a costly and complex undertaking. The idea had its skeptics, but Hood viewed the effort as crucial to creating information-based medicine and, ultimately, treating disease at the genetic level. His view prevailed, and the project famously completed its full map of the human genome in 2003.

With this vast wealth of information in hand, Hood is pushing a new approach to medicine that he calls P4—predictive, personalized, preventive, and participatory. "The foundation of P4 medicine is the idea that in the near future we will have the tools to reduce enormously complex data from 300 million Americans to simple hypotheses about health and disease for each individual," he says. So far the payoff for treating genetic disease has been scant. But a flurry of recent breakthroughs has made Hood, now president of the Institute for Systems Biology in Seattle, hopeful that his elegant new techniques for mining the genome and studying its interplay with the environment will soon transform medicine.

You have said that medicine is at the edge of an "information revolution." Can you explain?
In less than a decade, each of us will be surrounded by a virtual cloud of billions of points of medical data. Genome sequencing will cost only a few hundred dollars, so that will become a part of the medical record of each individual. A fraction of a drop of blood will be used to measure 2,500 blood proteins that assess the possibility of disease in each of your 50 major organs. Medicine will be personalized and preventive: Your genome might predict that you have an 80 percent chance of breast cancer by the time you are 50, but if you take a preventive drug starting when you are 40, the chance will drop to 2 percent. We will have the computational tools to connect all this information so we can gain enormous insights into health and disease and fashion an unbelievably predictive medicine of the future.

What prompted you to push for the Human Genome Project 25 years ago?
I realized we couldn't understand complexity one gene or one protein at a time; we needed a parts list of every human gene and the protein it coded for. My group at Caltech [where Hood worked at the time] had developed the enabling technology to analyze the genome, an automated DNA sequencer that uses fluorescent dyes to color-code the four different bases—the As, Cs, Ts, and Gs—that make up a strand of DNA. It's like having a pearl necklace with four different-colored beads on it. If you could snip them off one at a time and determine their colors, you could order the beads on the necklace. By ordering the beads, we determine the DNA sequence for a given gene.

How else have you helped advance the genomics revolution?
Two of our faculty members at the University of Washington [another of Hood's previous homes] invented the first key methods for proteomics, the study of proteins found in a cell, an organ, or an individual organism. We developed a high-speed cell sorter to separate different types of cells. We also helped develop DNA arrays—-chips containing short sequences of DNA that match up with parts of genes. For any given cell or tissue sample, these arrays can probe for the genes essential for understanding the underlying state of wellness or disease.

In 2000 you left academia to found the not-for-profit Institute for Systems Biology. Why?
The Human Genome Project gave us a parts list of genes and their proteins, but we still needed to understand them in the context of the entire biological system. This includes the networks that connect the genes and proteins, organizing them into cells, tissues, organs, individuals, and populations. At each of these levels, the environment impinges on the signal coming from the DNA and changes it. The grand fallacy back then was that genomics could give us the answer to everything. It can give some insights, but unless you put them together with other levels of information, you can't understand what's going on. That integration is "systems biology."

This year, your team and another at Baylor College of Medicine published landmark studies linking a specific gene with a specific disease by sequencing the genomes of an entire family in which that disease occurs. What did you do?
Past studies looked at large populations of unrelated individuals and came up with long lists of genes that could be categorized as behaving in unusual ways in a particular disease. But there were so many DNA sequencing errors imposed by the equipment, it was difficult to determine which gene caused the disease. A year ago we started thinking, why don't we select a single family with an interesting disease and see whether studying a smaller group of related individuals makes it possible to identify the genes involved in that disease. In the family we chose, the mother and father were healthy, but the two children each had two single-gene diseases: -ciliary dyskinesia, in which the defective gene was known, and Miller's syndrome, a craniofacial defect for which the causative gene was unknown. Our analysis located the gene causing Miller's syndrome. This is important because it shows that we can find the genetic cause of diseases—even common diseases involving many mutations—if we sequence family genomes.

Why did looking at a single family yield information that you could not get from earlier studies of large groups?
With a single family, we can use the principles of Mendelian genetics to correct more than 70 percent of the DNA sequencing errors caused by the equipment and the chemistry. How? If you know the mother's genome and the father's genome and you see that the children have some genes that neither parent has, then you know that difference is either a mutation or a processing error. When we did this correction, we were finally able to study models of genetic disease. It's that simple. We live and learn.

Will you now use family genome sequencing to study other, more common and complex diseases?

We've already picked another single-gene trait, Huntington's disease. After that, we plan to study Alzheimer's, which is really a whole series of diseases. Before we can find the genes involved, we have to stratify Alzheimer's patients into distinct types. So far we've identified about 100 blood proteins specific to the brain. Each of those proteins represents the operation of the brain network that synthesized it. If a brain is normal, each of those proteins will have one level of expression. But if the brain is diseased, a subset of those proteins will have their concentration changed. Each form of Alzheimer's disease should perturb different brain networks and so influence the concentration of different proteins that can be measured in the blood.

How will your P4 concept change the overall shape of health care?

The systems approach will take medicine from a focus on disease to a predictive, personalized, preventive, and participatory mode that focuses on wellness. That shift will reverse ever-escalating medical costs to the point where I think we can export P4 medicine to the undeveloped world and will make possible a democratization of health care that was absolutely inconceivable even five years ago.

FROM THE JULY-AUGUST 2010 ISSUE

Discover Interview: The Dark Hunter

Physicist Elena Aprile is certain that dark matter exists. She just hasn't found it yet.

By Fred Guterl | Wednesday, November 17, 2010

RELATED TAGS: DARK MATTER, SUBATOMIC PARTICLES

At Columbia University's Nevis Laboratories in Irvington, New York, Elena Aprile sits in front of a new liquid-xenon-filled detector that is key to her search for dark matter.

Doron Gild

Dark matter sounds like some physicist's tall tale: There's this invisible matter, see, and it has this powerful gravitational effect on galaxies. That's why we know it exists. In fact, it outweighs ordinary matter by about five to one. Problem is, dark matter doesn't reflect or absorb light, so we can't see it. Oh, and it rarely interacts with conventional atoms, so we can't feel it, either. However, we know it makes up a huge part of the universe, so we keep looking for it.

As mind-bending (and perhaps logic-challenging) as these ideas may seem, a lot of physicists are searching for this elusive matter. Elena Aprile is one of the leading lights in this dark business. She heads a prominent dark matter experiment called Xenon, which is based 5,000 feet underground in Italy's Laboratori Nazionali del Gran Sasso, one of the world's largest subterranean physics labs. Aprile, who is also a codirector of Columbia University's Astrophysics Lab, started the project in 2007 with a detector called Xenon10. Since then she has upgraded to the more sensitive Xenon100. "I feel proud to have one of the best instruments in the field for detecting dark matter," Aprile says of Xenon100. But the huge questions remain: What is dark matter, and how close are scientists to finding it? Aprile recently updated DISCOVER on how things are going in her search for the missing majority of the universe.

Seriously—what is dark matter?

The best answer is that we have no idea. We know dark matter is there. We've known it for more than 70 years. There was a 1933 paper by the Swiss astronomer Fritz Zwicky showing that visible matter is only a small fraction of the universe. Just 18 percent of the matter in the universe is composed of the stuff we know. The remaining 82 percent is what we call dark matter. Other discoveries in astronomy have since reinforced this view that something is missing. We know dark matter is there, but only from its gravitational effects. For example, the presence of dark matter helps explain why our galaxy is stable. The Milky Way is a disk that rotates like a merry-go-round. The question is, what keeps it from flying apart? Gravity, of course, but there is not enough visible matter in the galaxy to account for the amount of gravity needed to hold it together. That's why we know that there must be other matter there that we can't see.

What is dark matter composed of?
We think it's made of a type of particle that doesn't like to interact with normal matter [protons, neutrons, and other types of particles] very often. And it's very heavy, very massive. Perhaps as heavy as an entire lead atom or even heavier. It's probably a relic particle from the Big Bang, a member of a family of particles that we've named weakly interacting massive particles, or WIMPs.

How do we know dark matter consists of some new kind of particle?
Actually, we might be on the wrong track in thinking that dark matter is composed of a fundamentally new type of particle. That's why we call it "the WIMP miracle." The so-called standard model of particle physics, which lays out the way physicists think the universe works, has deficiencies. A lot of things, a lot of data, don't fit. We have theories, such as supersymmetry and extra dimensions, that have been put forward to explain the things that are missing from the standard model or that don't fit with the data we get. Some of the particles predicted by those theories are natural candidates to be dark matter because they have all the right characteristics. A particle called the neutralino, for instance, is a type of WIMP that's a perfect candidate for dark matter in part because it doesn't interact with other particles much, and that would explain why nobody has yet detected it.

If WIMPS don't interact much with other particles, how can you find them?
The way we go about this search is to wait for a particle of dark matter to come into contact with our device, which is basically a pot of liquid xenon [an element that is used, in gas form, in the very bright headlights of many new cars] sandwiched between two detectors. We use xenon because it is one of the heaviest elements—meaning that each atom contains a lot of protons and neutrons—and that increases the odds that dark matter will interact with it. Whenever that happens, whenever a WIMP gets stuck in there, the xenon displays some remarkable properties. There will be a flash or scintillation of ultraviolet light. You can't see it with the naked eye, so to detect this light, we have 178 extremely sensitive one-pixel cameras, called photomultipliers, above and below the liquid-xenon-filled detector. We also look for an ionization signal: If a dark matter particle rubs against a xenon atom, there will be electrons liberated and a charge produced. Those electrons drift upward through the liquid xenon to a positively charged anode [electric terminal], which produces a second flash of light that the cameras will detect.

That signal would tell you that a WIMP has finally made contact?
Well, we can extract a wealth of information from those two signals, including the speed of the particle, the location of the interaction, and the type of particle it was—an electron, a neutron, or dark matter. The more gently the particle touches the xenon, the more likely that it's a WIMP.

But you haven't definitely found one yet?
No. I mean, it constantly happens that you look at something and say, "Hey, what's this?" and you think it could be dark matter. But we have always found an explanation for these events. Still, it's important to consider the possibility that we might actually be looking right in the eye of dark matter.

How close are we to finding dark matter? Have others had hits, or possible hits?
There was news in December (article; live-blog) that another group of researchers, the Cryogenic Dark Matter Search (CDMS), had detected dark matter in a mine in Minnesota, but they saw a very weak signal. They recorded two events that they cannot fully explain as background noise. One of the events is very close to the threshold of noise. It's not a detection; the collaboration itself doesn't call it that. It's the hint of a detection. There was initially a lot of excitement, but that has died down.

As for our group, we have collected data for several months now with Xenon100 and will continue through the summer. This powerful detector has the lowest background noise ever measured for any dark matter detector, and it is the largest-scale detector in operation. If the signal CDMS found was truly from dark matter, we'll easily be able to confirm it this year. At the same time, particle physicists are looking for dark matter with the Large Hadron Collider in Geneva. We're hoping they can tell us more about these particles in the next few years.

What is it like to search for something that you may never find?

It feels very exciting and almost like a duty. The fact that we don't know if we will discover dark matter does not take away the necessity to try. The Italian particle physicist Carlo Rubbia, who was my doctoral thesis adviser at the University of Geneva, recently quoted Galileo at a conference on dark matter: Provando et riprovando—"Try and try again." This is the basis of experimental science. We must try and try again to find the truth. If we stop because there is no guarantee that we will find anything, then we would never find anything again. In fact, in terms of dark matter, not finding anything is extremely important because it will make us find new roads to explore. We must keep searching for it with the best tools we have.

FROM THE APRIL 2011 ISSUE

Discover Interview: Lynn Margulis Says She's Not Controversial, She's Right

It's the neo-Darwinists, population geneticists, AIDS researchers, and English-speaking biologists as a whole who have it all wrong.

By Dick Teresi | Friday, June 17, 2011

RELATED TAGS: EVOLUTION, ANIMAL INTELLIGENCE, HUMAN EVOLUTION, GENETICS, SEX & REPRODUCTION, ECOSYSTEMS

photography by Bob O'Connor

A conversation with Lynn Margulis is an effective way to change the way you think about life. Not just your life. All life. Scientists today recognize five groups of life: bacteria, protoctists (amoebas, seaweed), fungi (yeast, mold, mushrooms), plants, and animals. Margulis, a self-described "evolutionist," makes a convincing case that there are really just two groups, bacteria and everything else.

That distinction led to her career-making insight. In a 1967 paper published in the *Journal of Theoretical Biology*, Margulis suggested that mitochondria and plastids—vital structures within animal and plant cells—evolved from bacteria hundreds of million of years ago, after bacterial cells started to collect in interactive communities and live symbiotically with one another. The resulting mergers yielded the compound cells known as eukaryotes, which in turn gave rise to all the rest—the protoctists, fungi, plants, and animals, including humans. The notion that we are all the children of bacteria seemed outlandish at the time, but it is now widely supported and accepted. "The evolution of the eukaryotic cells was the single most important event in the history of the organic world," said Ernst Mayr, the leading evolutionary biologist of the last century. "Margulis's contribution to our understanding the symbiotic factors was of enormous importance."

Her subsequent ideas remain decidedly more controversial. Margulis came to view symbiosis as the central force behind the evolution of new species, an idea that has been dismissed by modern biologists. The dominant theory of evolution (often called neo-Darwinism) holds that new species arise through the gradual accumulation of random mutations, which are either favored or weeded out by natural selection. To Margulis, random mutation and natural selection are just cogs in the gears of evolution; the big leaps forward result from mergers between different kinds of organisms, what she calls symbiogenesis. Viewing life as one giant network of social connections has set Margulis against the mainstream in other high-profile ways as well. She disputes the current medical understanding of AIDS and considers every kind of life to be "conscious" in a sense.

Margulis herself is a highly social organism. Now 71, she is a well-known sight at the University of Massachusetts at Amherst, where she is on the geosciences faculty, riding her bike in all weather and at all times of day. Interviewer Dick Teresi, a neighbor, almost ran her over when, dressed in a dark coat, she cycled in front of his car late at night. On the three occasions that they met for this interview, Teresi couldn't help noticing that Margulis shared her home with numerous others: family, students, visiting scholars, friends, friends of friends, and anybody interesting who needed a place to stay.

Most scientists would say there is no controversy over evolution. Why do you disagree?
All scientists agree that evolution has occurred—that all life comes from a common ancestry, that there has been extinction, and that new taxa, new biological groups, have arisen. The question is, is natural selection enough to explain evolution? Is it the driver of evolution?

And you don't believe that natural selection is the answer?
This is the issue I have with neo-Darwinists: They teach that what is generating novelty is the accumulation of random mutations in DNA, in a direction set by natural selection. If you want bigger eggs, you keep selecting the hens that are laying the biggest eggs, and you get bigger and bigger eggs. But you also get hens with defective feathers and wobbly legs. Natural selection eliminates and maybe maintains, but it doesn't create.

That seems like a fairly basic objection. How, then, do you think the neo-Darwinist perspective became so entrenched?
In the first half of the 20th century, neo-Darwinism became the name for the people who reconciled the type of gradual evolutionary change described by Charles Darwin with Gregor Mendel's rules of heredity [which first gained widespread recognition around 1900], in which fixed traits are passed from one generation to the next. The problem was that the laws of genetics showed stasis, not change. If you have pure breeding red flowers and pure breeding white flowers, like carnations, you cross them and you get pink flowers. You back-cross them to the red parent and you could get three-quarters red, one-quarter white. Mendel showed that the grandparent flowers and the offspring flowers could be identical to each other. There was no change through time.

There's no doubt that Mendel was correct. But Darwinism says that there has been change through time, since all life comes from a common ancestor—something that appeared to be supported when, early in the 20th century, scientists discovered that X-rays and specific chemicals caused mutations. But did the neo-Darwinists ever go out of their offices? Did they or their modern followers, the population geneticists, ever go look at what's happening in nature the way Darwin did? Darwin was a fine naturalist. If you really want to study evolution, you've got go outside sometime, because you'll see symbiosis everywhere!

So did Mendel miss something? Was Darwin wrong?
I'd say both are incomplete. The traits that follow Mendel's laws are trivial. Do you have a widow's peak or a straight hairline? Do you have hanging earlobes or attached earlobes? Are you female or male? Mendel found seven traits that followed his laws exactly. But neo-Darwinists say that new species emerge when mutations occur and modify an organism. I was taught over and over again that the accumulation of random mutations led to evolutionary change—led to new species. I believed it until I looked for evidence.

What kind of evidence turned you against neo-Darwinism?
What you'd like to see is a good case for gradual change from one species to another in the field, in the laboratory, or in the fossil record—and preferably in all three. Darwin's big mystery was why there was no record at all before a specific point [dated to 542 million years ago by modern researchers], and then all of a sudden in the fossil record you get nearly all the major types of animals. The paleontologists Niles Eldredge

Stephen Jay Gould studied lakes in East Africa and on Caribbean islands looking for Darwin's gradual change from one species of trilobite or snail to another. What they found was lots of back-and-forth variation in the population and then—whoop—a whole new species. There is no gradualism in the fossil record.

Gould used the term "punctuated equilibrium" to describe what he interpreted as actual leaps in evolutionary change. Most biologists disagreed, suggesting a wealth of missing fossil evidence yet to be found. Where do you stand in the debate?
"Punctuated equilibrium" was invented to describe the discontinuity in the appearance of new species, and symbiogenesis supports the idea that these discontinuities are real. An example: Most clams live in deep, fairly dark waters. Among one group of clams is a species whose ancestors ingested algae—a typical food—but failed to digest them and kept the algae under their shells. The shell, with time, became translucent, allowing sunlight in. The clams fed off their captive algae and their habitat expanded into sunlit waters. So there's a discontinuity between the dark-dwelling, food-gathering ancestor and the descendants that feed themselves photosynthetically.

What about the famous "beak of the finch" evolutionary studies of the 1970s? Didn't they vindicate Darwin?
Peter and Rosemary Grant, two married evolutionary biologists, said, 'To hell with all this theory; we want to get there and look at speciation happening.' They measured the eggs, beaks, et cetera, of finches on Daphne Island, a small, hilly former volcano top in Ecuador's Galápagos, year after year. They found that during floods or other times when there are no big seeds, the birds with big beaks can't eat. The birds die of starvation and go extinct on that island.


photography by Bob O'Connor

Did the Grants document the emergence of new species?
They saw this big shift: the large-beaked birds going extinct, the small-beaked ones spreading all over the island and being selected for the kinds of seeds they eat. They saw lots of variation within a species, changes over time. But they never found any new species—ever. They would say that if they waited long enough they'd find a new species.

Some of your criticisms of natural selection sound a lot like those of Michael Behe, one of the most famous proponents of "intelligent design," and yet you have debated Behe. What is the difference between your views?
The critics, including the creationist critics, are right about their criticism. It's just that they've got nothing to offer but intelligent design or "God did it." They have no alternatives that are scientific.

You claim that the primary mechanism of evolution is not mutation but symbiogenesis, in which new species emerge through the symbiotic relationship between two or more kinds of organisms. How does that work?
All visible organisms are products of symbiogenesis, without exception. The bacteria are the unit. The way I

think about the whole world is that it's like a pointillist painting. You get far away and it looks like Seurat's famous painting of people in the park (jpg). Look closely: The points are living bodies—different distributions of bacteria. The living world thrived long before the origin of nucleated organisms [the eukaryotic cells, which have genetic material enclosed in well-defined membranes]. There were no animals, no plants, no fungi. It was an all-bacterial world—bacteria that have become very good at finding specialized niches. Symbiogenesis recognizes that every visible life-form is a combination or community of bacteria.

How could communities of bacteria have formed completely new, more complex levels of life?
Symbiogenesis recognizes that the mitochondria [the energy factories] in animal, plant, and fungal cells came from oxygen-respiring bacteria and that chloroplasts in plants and algae—which perform photosynthesis—came from cyanobacteria. These used to be called blue-green algae, and they produce the oxygen that all animals breathe.

Are you saying that a free-living bacterium became part of the cell of another organism? How could that have happened?
At some point an amoeba ate a bacterium but could not digest it. The bacterium produced oxygen or made vitamins, providing a survival advantage to both itself and the amoeba. Eventually the bacteria inside the amoeba became the mitochondria. The green dots you see in the cells of plants originated as cyanobacteria. This has been proved without a doubt.

And that kind of partnership drives major evolutionary change?
The point is that evolution goes in big jumps. That idea has been called macromutation, and I was denigrated in 1967 at Harvard for mentioning it. "You believe in macromutation? You believe in acquired characteristics?" the important professor Keith Porter asked me with a sneer. No, I believe in acquired genomes.

Can you give an example of symbiogenesis in action?
Look at this cover of *Plant Physiology* [a major journal in the field]. The animal is a juvenile slug. It has no photosynthesis ancestry. Then it feeds on algae and takes in chloroplasts. This photo is taken two weeks later. Same animal. The slug is completely green. It took in algae chloroplasts, and it became completely photosynthetic and lies out in the sun. At the end of September, these slugs turn red and yellow and look like dead leaves. When they lay eggs, those eggs contain the gene for photosynthesis inside. Or look at a cow. It is a 40-gallon fermentation tank on four legs. It cannot digest grass and needs a whole mess of symbiotic organisms in its overgrown esophagus to digest it. The difference between cows and related species like bison or musk ox should be traced, in part, to the different symbionts they maintain.

But if these symbiotic partnerships are so stable, how can they also drive evolutionary change?
Symbiosis is an ecological phenomenon where one kind of organism lives in physical contact with another. Long-term symbiosis leads to new intracellular structures, new organs and organ systems, and new species as one being incorporates another being that is already good at something else. This major mode of evolutionary innovation has been ignored by the so-called evolutionary biologists. They think they own evolution, but they're basically anthropocentric zoologists. They're playing the game while missing four out of five of the cards. The five are bacteria, protoctists, fungi, animals, and plants, and they're playing with just animals—a fifth of the deck. The evolutionary biologists believe the evolutionary pattern is a tree. It's not. The evolutionary pattern is a web—the branches fuse, like when algae and slugs come together and stay together.

In contrast, the symbiotic view of evolution has a long lineage in Russia, right?
From the very beginning the Russians said natural selection was a process of elimination and could not produce all the diversity we see. They understood that symbiogenesis was a major source of innovation, and they rejected Darwin. If the English-speaking world owns natural selection, the Russians own symbiogenesis. In 1924, this man Boris Mikhaylovich Kozo-Polyansky wrote a book called *Symbiogenesis: A New Principle of Evolution*, in which he reconciled Darwin's natural selection as the eliminator and symbiogenesis as the innovator. Kozo-Polyansky looked at cilia—the wavy hairs that some microbes use to move—and said it is not beyond the realm of possibility that cilia, the tails of sperm cells, came from "flagellated cytodes," by which he clearly meant swimming bacteria.

Has that idea ever been verified?
The sense organs of vertebrates have modified cilia: The rods and cone cells of the eye have cilia, and the balance organ in the inner ear is lined with sensory cilia. You tilt your head to one side and little calcium carbonate stones in your inner ear hit the cilia. This has been known since shortly after electron microscopy came in 1963. Sensory cilia did not come from random mutations. They came by acquiring a whole genome of a symbiotic bacterium that could already sense light or motion. Specifically, I think it was a spirochete [a corkscrew-shaped bacterium] that became the cilium.

Don't spirochetes cause syphilis?
Yes, and Lyme disease. There are many kinds of spirochetes, and if I'm right, some of them are ancestors to the cilia in our cells. Spirochete bacteria are already optimized for sensitivity to motion, light, and chemicals. All eukaryotic cells have an internal transport system. If I'm right, the whole system—called the cytoskeletal system—came from the incorporation of ancestral spirochetes. Mitosis, or cell division, is a kind of internal motility system that came from these free-living, symbiotic, swimming bacteria. Here [she shows a video] we compare isolated swimming sperm tails to free-swimming spirochetes. Is that clear enough?

And yet these ideas are not generally accepted. Why?
Do you want to believe that your sperm tails come from some spirochetes? Most men, most evolutionary biologists, don't. When they understand what I'm saying, they don't like it.

We usually think of bacteria as strictly harmful. You disagree?
We couldn't live without them. They maintain our ecological physiology. There are vitamins in bacteria that you could not live without. The movement of your gas and feces would never take place without bacteria. There are hundreds of ways your body wouldn't work without bacteria. Between your toes is a jungle; under your arms is a jungle. There are bacteria in your mouth, lots of spirochetes, and other bacteria in your intestines. We take for granted their influence. Bacteria are our ancestors. One of my students years ago cut himself deeply with glass and accidentally inoculated himself with at least 10 million spirochetes. We were all scared but nothing happened. He didn't even have an allergic reaction. This tells you that unless these microbes have a history with people, they're harmless.

Are you saying that the only harmful bacteria are the ones that share an evolutionary history with us?
Right. Dangerous spirochetes, like the *Treponema* of syphilis or the *Borrelia* of Lyme disease, have long-standing symbiotic relationships with us. Probably they had relationships with the prehuman apes from which

humans evolved. *Treponema* has lost four-fifths of its genes, because you're doing four-fifths of the work for it. And yet people don't want to understand that chronic spirochete infection is an example of symbiosis.

You have upset many medical researchers with the suggestion that corkscrew-shaped spirochetes turn into dormant "round bodies." What's that debate all about?

Spirochetes turn into round bodies in any unfavorable condition where they survive but cannot grow. The round body is a dormant stage that has all the genes and can start growing again, like a fungal spore. Lyme disease spirochetes become round bodies if you suspend them in distilled water. Then they come out and start to grow as soon as you put them in the proper food medium with serum in it. The common myth is that penicillin kills spirochetes and therefore syphilis is not a problem. But syphilis is a major problem because the spirochetes stay hidden as round bodies and become part of the person's very chemistry, which they commandeer to reproduce themselves. Indeed, the set of symptoms, or syndrome, presented by syphilitics overlaps completely with another syndrome: AIDS.

Wait—you are suggesting that AIDS is really syphilis?

There is a vast body of literature on syphilis spanning from the 1500s until after World War II, when the disease was supposedly cured by penicillin. Yet the same symptoms now describe AIDS perfectly. It's in our paper "Resurgence of the Great Imitator." Our claim is that there's no evidence that HIV is an infectious virus, or even an entity at all. There's no scientific paper that proves the HIV virus causes AIDS. Kary Mullis [winner of the 1993 Nobel Prize for DNA sequencing, and well known for his unconventional scientific views] said in an interview that he went looking for a reference substantiating that HIV causes AIDS and discovered, "There is no such document."

Syphilis has been called "the great imitator" because patients show a whole range of symptoms in a given order. You have a genital chancre, your symptoms go away, then you have the pox, this skin problem, and then it's chronic, and you get sicker and sicker. The idea that penicillin kills the cause of the disease is nuts. If you treat the painless chancre in the first few days of infection, you may stop the bacterium before the symbiosis develops, but if you really get syphilis, all you can do is live with the spirochete. The spirochete lives permanently as a symbiont in the patient. The infection cannot be killed because it becomes part of the patient's genome and protein synthesis biochemistry. After syphilis establishes this symbiotic relationship with a person, it becomes dependent on human cells and is undetectable by any testing.

Is there a connection here between syphilis and Lyme disease, which is also caused by a spirochete and which is also said to be difficult to treat when diagnosed late?

Both the *Treponema* that cause syphilis and the *Borrelia* that cause Lyme disease contain only a fifth of the genes they need to live on their own. Related spirochetes that can live outside by themselves need 5,000 genes, whereas the spirochetes of those two diseases have only 1,000 in their bodies. The 4,000 missing gene products needed for bacterial growth can be supplied by wet, warm human tissue. This is why both the Lyme disease *Borrelia* and syphilis *Treponema* are symbionts—they require another body to survive. These *Borrelia* and *Treponema* have a long history inside people. Syphilis has been detected in skull abnormalities going back to the ancient Egyptians. But I'm interested in spirochetes only because of our ancestry. I'm not interested in the diseases.

When you talk about the evolutionary intelligence of bacteria, it almost sounds like you think of them as conscious beings.

I do think consciousness is a property of all living cells. All cells are bounded by a membrane of their own making. To sense chemicals—food or poisons—it takes a cell. To have a sense of smell takes a cell. To sense light, it takes a cell. You have to have a bounded entity with photoreceptors inside to sense light. Bacteria are conscious. These bacterial beings have been around since the origin of life and still are running the soil and the air and affecting water quality.

Your perspective is rather humbling.
The species of some of the protoctists are 542 million years old. Mammal species have a mean lifetime in the fossil record of about 3 million years. And humans? You know what the index fossil of *Homo sapiens* in the recent fossil record is going to be? The squashed remains of the automobile. There will be a layer in the fossil record where you're going to know people were here because of the automobiles. It will be a very thin layer.

Do we overrate ourselves as a species?
Yes, but we can't help it. Look, there are nearly 7,000 million people on earth today and there are 10,000 chimps, and the numbers are getting fewer every day because we're destroying their habitat. Reg Morrison, who wrote a wonderful book called *The Spirit in the Gene*, says that although we're 99 percent genetically in common with chimps, that 1 percent makes a huge difference. Why? Because it makes us believe that we're the best on earth. But there is lots of evidence that we are "mammalian weeds." Like many mammals, we overgrow our habitats and that leads to poverty, misery, and wars.

Why do you have a reputation as a heretic?
Anyone who is overtly critical of the foundations of his science is persona non grata. I am critical of evolutionary biology that is based on population genetics. I call it zoocentrism. Zoologists are taught that life starts with animals, and they block out four-fifths of the information in biology [by ignoring the other four major groups of life] and all of the information in geology.

You have attacked population genetics—the foundation of much current evolutionary research —as "numerology." What do you mean by that term?
When evolutionary biologists use computer modeling to find out how many mutations you need to get from one species to another, it's not mathematics—it's numerology. They are limiting the field of study to something that's manageable and ignoring what's most important. They tend to know nothing about atmospheric chemistry and the influence it has on the organisms or the influence that the organisms have on the chemistry. They know nothing about biological systems like physiology, ecology, and biochemistry. Darwin was saying that changes accumulate through time, but population geneticists are describing mixtures that are temporary. Whatever is brought together by sex is broken up in the next generation by the same process. Evolutionary biology has been taken over by population geneticists. They are reductionists ad absurdum. Population geneticist Richard Lewontin gave a talk here at UMass Amherst about six years ago, and he mathematized all of it—changes in the population, random mutation, sexual selection, cost and benefit. At the end of his talk he said, "You know, we've tried to test these ideas in the field and the lab, and there are really no measurements that match the quantities I've told you about." This just appalled me. So I said, "Richard Lewontin, you are a great lecturer to have the courage to say it's gotten you nowhere. But then why do you continue to do this work?" And he looked around and said, "It's the only thing I know how to do, and if I don't do it I won't get my grant money." So he's an honest man, and that's an honest answer.

Do you ever get tired of being called controversial?

I don’t consider my ideas controversial. I consider them right.

FROM THE JULY-AUGUST 2011 ISSUE

Discover Interview: Anton Zeilinger Dangled From Windows, Teleported Photons, and Taught the Dalai Lama

What started out as totally intellectual, impractical experiments could help pave the way for a revolution in computing.

By Eric Powell | Monday, August 29, 2011

RELATED TAGS: SUBATOMIC PARTICLES, EINSTEIN, LIGHT

In Anton Zeilinger's dream world, superfast quantum computers will process data using single atoms instead of silicon chips. Such devices will have fantastic powers, including the ability to transpose matter into packets of information and teleport it through space. But to Zeilinger, even that dream is not exotic enough. When science is truly new, he says, the technology that results from it "cannot be imagined" in advance.

He speaks from experience: The Austrian physicist has spent his career on the outer boundaries of understanding, studying some of the greatest mysteries of quantum physics. While classic Newtonian physics does a fine job of describing the world we see around us, it breaks down utterly when confronted with the unpredictable behavior of the quantum world, the realm of atoms and quarks. Quantum physics addresses that breakdown, but it also leads to ideas so bizarre that Albert Einstein said they had to be in error. He particularly objected to "entanglement"—the notion that twin particles could become intertwined across space and time—and predicted it would never be proved.

Yet Zeilinger is doing just that through an elaborate series of experiments, each one cleverer than the last. In his hands, entanglement is not just a scientific oddity but an essential tool. Using photons, the basic unit of light, he demonstrated that multiple particles could be entangled, a key step toward practical quantum computers. He also was the first to accomplish teleportation (pdf), in which the characteristics of one particle are transferred to another, a breakthrough that could lead to the creation of unbreakable codes. A professor of physics at the University of Vienna and scientific director of the Institute of Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Zeilinger was awarded the first Newton Medal, given by the British Institute of Physics, and the 2010 Wolf Prize in Physics. DISCOVER senior editor Eric Powell caught up with him during a visit to New York City.

How did you come to view the world in such an unusual way?
I grew up after World War II in Austria, so we were very poor. We lived in the Soviet zone, which meant housing was scarce. We were put up on the third floor of a castle in a small village. It had these huge rooms, and I liked to look out the window. So my parents got these bars on the window, and they tied me to them with a harness. I would sit there, hanging out of the window for hours just watching and observing cows and people below. The villagers still talk about the strange child hanging from the castle window watching everything.

So you were intensely curious from an early age?
Oh, I used to take apart everything I could. Like my sister's dolls. I took the arms and the legs off because I

wanted to know how they worked, and I never put things back together, which was not always appreciated, as you can imagine. And later in school I had a very good physics and mathematics teacher. He was able to teach us the basic ideas of relativity theory, such that we believed we understood it, which I now know is not true. Then I learned about quantum mechanics on my own at university, from books, and I was immediately struck by its mathematical beauty.

When did you become interested in entanglement?
In the late 1970s, after I came to MIT, I read the famous 1935 Einstein-Podolsky-Rosen paper, which criticized quantum mechanics as incomplete and first raised the idea of quantum entanglement as a thought experiment. If entanglement was correct, Einstein and his coauthors argued, then two particles would be connected over large distances in such a way that by measuring the properties of one you could predict the properties of the other. But, they argued, this scenario violated the Heisenberg uncertainty principle, which said that it's impossible to know both the position and momentum of a particle at the same time [because the act of measuring one instantly and unavoidably changes the other]. Because the two theories were at odds with each other, they said, quantum mechanics must be incomplete.

Some vital element was missing, you mean?
That's what they argued. They said that physics has to be about things really existing out there independent of our doing a measurement; that was the basic tenet of Einstein all his life. Today we know that the argument was wrong.

And how do we know that?
Thanks to physicist John Bell, who took quantum entanglement seriously. Bell developed a mathematical proof called Bell's theorem to test the thought experiment Einstein had suggested, which was based on the assumptions of a theory called local realism. In local realism, it is assumed that particles carry properties independent of observation, and that no information can travel faster than the speed of light between the particles. This leads to experimental predictions conflicting with quantum mechanics, which states that the very act of measuring a particle changes the properties measured and that this change happens faster than light. But back when Bell created his proof, it wasn't possible to do a real-world experiment that could decide between local realism and quantum mechanics.

Today you can test Bell's theorem in the laboratory with entangled particles. What do these experiments conclude?
That local realism doesn't work. For example, say you are experimenting with entangled photons. As soon as you measure one of the entangled photons in a detector and find that its polarization—that is, the orientation of its waves—is horizontal, the other one in the pair is instantly projected into a horizontal state. And this happens not because the photons were both horizontally polarized from the beginning. That is contradicted by the experiments. It doesn't matter whether you look at the two particles at the same time, separated over large distances, or one after the other; the results are the same. So it seems as if quantum mechanics doesn't care about space and time.

So does that mean Einstein was wrong?
There are still some technical loopholes in the experiments testing Bell's theorem that could allow for a local realistic explanation of entanglement. For instance, we don't detect all the particles in an experiment, and therefore it is conceivable that, were we to detect every single particle, some would not be in agreement with

quantum mechanics. There is a very remote chance that nature is really vicious and that it allows us to detect only particles that agree with quantum mechanics. If so, and if we could ever detect the others, then local realism could be saved. But I think we are close to closing all of these loopholes, which would be a significant achievement with practical implications for quantum technologies.

Your own experiments with entangled particles took off in the 1980s, through your collaboration with theoretical physicist Daniel Greenberger. How did that come about?
Daniel came to Vienna on a Fulbright Fellowship that I had organized for him. I remember the first morning we were sitting there together and we were thinking, "What shall we work on?" It turned out that we both had been asking ourselves how we could extend Bell's theorem to new domains where it hadn't been applied yet. And we both thought it might be interesting to investigate whether or not more than two particles could be entangled.

No one else had considered that type of experiment?
Nobody had worked on entanglement with more than two particles, though the approach is kind of obvious in hindsight. People have worked with two photons, so why not three, you know? We discovered that multiparticle entangled states could exist in theory [some of them are now called Greenberger-Horne-Zeilinger, or GHZ, states], and I decided that my goal was to realize them in the laboratory. And it turns out that most of the tools you need to create them simply did not exist. The light sources and detectors were not good enough to observe multiparticle entanglement. A lot had to be done.

How were you eventually able to create these states?
We found a way. To do this you need four photons—two photons entangled in one state and the other two photons entangled in another state. Then we send one photon from each pair into a detector, and you measure only one in such a way that you don't know where this one photon you measure came from, from the first pair or from the second pair. If you do that right, the remaining three photons end up being entangled.

On the way to creating multiparticle entangled states, you also found a way to transfer the properties of one particle to another—the closest thing to teleportation we have. How did you become interested in that?
Well, that's actually a funny story. In 1993 a proposal by theoretical physicists came out about quantum teleportation, basically the transfer of one particle's properties to another that could be arbitrarily far away. When I read this I said, "What are they are talking about? This is a typical theoreticians' proposal; they don't have any idea how impossible this experiment is."

What were the theorists proposing?
They had a simple thought experiment. You have two individuals, by convention we call them Bob and Alice, who want to communicate via entangled pairs of particles. Alice has a quantum state, which can represent a particular piece of information, and she wants to transfer this quantum state to Bob. And let's suppose that the communication channels between the two are very bad, such that Alice cannot send the quantum state itself because it will be disturbed by the environment or whatever. These theoreticians proposed that the way to transfer that quantum state was to entangle a third particle with an already entangled pair. So if Alice has one particle from an entangled pair and Bob has the other, then what Alice does is entangle her particle with a third particle that carries the quantum state she wants to send to Bob. Just by doing this entangling procedure, the information carried by the third particle is teleported over to Bob's. This is a very elegant idea, but there was no way to do the experiment in the old days.

But on the road to realizing multiparticle entangled states, we actually ended up developing the tools that enabled us to do the teleportation experiment. This was amazing. For teleportation you have to start with two entangled photons, and then you have to be able to entangle one of those with a third photon. That's the idea. And the big surprise is that this has implications for the new field of quantum information science.

What is the connection between quantum teleportation and quantum computation?
A quantum computer needs what is called a universal quantum gate, a device where the quantum state of one system changes depending on the state of another system. It's similar to logic gates, the circuits that regulate output in classical computers. And teleportation can actually serve as that universal quantum gate.

Before this, what would you tell people if they asked you about the practical implications of your research into the fundamentals of quantum mechanics?
I would openly tell them that it had no use whatsoever.

You would say that you were just satisfying your natural curiosity?
This is part of being human. It must go back to prehistoric times when people stood there and looked up at the sky and wondered what's going on up there. We would not have our civilization if people weren't curious about things. To me this is the most important driving force in science. Even for developing new technology, if you really want to do something new, then by its very nature future technology cannot be imagined.

I mean, who had thought of the mobile phone? When the computer chip was developed, nobody had any idea that this would be in a mobile phone, that you would be able to see photographs of other people and download whole books. Our fantasies just aren't strong enough. We can imagine a lot about the future but they're usually the wrong things. If you look at things written in the 1950s about the future, most of it was simply wrong. And the same is true when people talk about the possible future today.

Some of your most recent work involved sending entangled photons across long distances in the Canary Islands. What did you get out of those experiments?
Well, two things. One is making progress in developing methodology for worldwide quantum communication with satellites, because the distance [from the ground to low-earth orbit] is about the same. The second is closing another loophole in Bell's theorem—the freedom of choice loophole. This loophole assumes that the source that creates the two particles in the experiment also somehow creates information that influences the choice of what measurement to make on the particles. This is a completely logically consistent position, and the way to rule it out is to make the decision of what to measure before any information can have reached you from the source.

To test this we designed an experiment on the two islands of La Palma and Tenerife, which are separated by 90 miles. On La Palma we created a pair of photons and sent one of the photons over to Tenerife using a free space telescope link, and on Tenerife we decided a long time before the photon arrived which polarization would be measured.

And when you say a long time, you mean. . .
A long time means that—for modern electronics, it's a long time—it takes half a millisecond for the photon to go from A to B, so if you decide something like a few tenths of a microsecond before, then that's a long time. Then the other photon is kept locally in a glass-fiber spool and measured at a later time in La Palma. And which ki

of measurement to perform on this photon is decided by a random-number generator at the same moment when the photon pairs are created at a distant location, about a mile away, which means that no signal could travel fast enough to influence this.

So were you able to close that loophole?
That loophole was closed, and now the big carrot is to do a definitive experiment that closes all loopholes at once. The most important point in closing all the loopholes is that it would lead to completely secure quantum cryptography. The loopholes can in principle be used by an eavesdropper to hide, to cover up his presence and get some of the information. But if you have a loophole-free test of Bell's theorem, then this is not possible anymore. So there is a practical consequence to these experiments.

What are the philosophical implications of your work?
The quantum state represents measurement results; it represents information about a concrete situation, and it allows me to make predictions about future measurement results. So it is information both about a situation that I know and information about the future. I often say that quantum theory is information theory, and that the separation between reality and information is an artificial one. You cannot think about reality without admitting that it's information you are handling. So we need a new concept that encompasses the two. We are not there yet.

Have any philosophers picked up on the conceptual implications of your research?
I have a program where I invite philosophers to see what goes on in the lab, because it changes your intuition. A great majority of philosophers are realists, though sometimes naive realists. I often ask them, "Why are you so realistic? If you analyze your fundamental notions you might conclude that these things are more counterintuitive than you think." Often the answer is, "Yes, but I want to describe reality." And then I say, "I also want to describe reality, but why are you not satisfied with describing the reality of the observations? Why do you want a hidden reality that exists independent of the observation?" And I don't get satisfactory answers.

What is the most fascinating new scientific question you see looming on the horizon?
To me the most interesting question is, how do we get to the next theory? I find it extremely unlikely that quantum mechanics will not be superseded some day by a deeper theory, because why not? So far in the history of physics we have always found something deeper. That deeper thing is usually more counterintuitive than what we had before and takes awhile to get used to. Just compare relativity theory [which postulates that time is relative and depends on the observer] to Newtonian space-time. This is part of the motivation for our experiments. We want to peel out in as much detail as possible what the conceptual issues are.

As a person who has spent a life with quantum mechanics, do you think you have a deeper sense of the absurd?
It could very well be. I've noticed that I'm less surprised by unexpected developments than many other people. I seem to take the unpredictability of things as more natural than many other people. When young people join my group, you can see them tapping around in the dark and not finding their way intuitively. But then after some time, two or three months, they get in step and they get this intuitive understanding of quantum mechanics, and it's actually quite interesting to observe. It's like learning to ride a bike. Sure, there's a lot of interesting physics behind it. But practical experience works too. It's the same in doing quantum experiments. People learn how to play with the stuff.

+

You have spent time with the Dalai Lama and have taught him the fundamentals of quantum mechanics. What was that like? Is he a good student?
He has a very clear scientific mind. He's very analytic, very precise. I explained the superposition principle and entanglement and the randomness of measurement events, and he always asked the right questions. I invited him to visit a laboratory in Innsbruck, which has ion traps for individual atoms, and you can usually look at an atom there. I wanted to show this to the Dalai Lama because he didn't believe in atoms. And interestingly, when he came it didn't work.

The Buddhism practiced by the Dalai Lama embraces an unbroken chain of cause and effect. How did he respond when you explained the random nature of quantum events?
This was something he didn't like. He said, "You have to look closely, you have to find the cause." And then he said something interesting: "If this is really true and you can convince us, then we have to change our teaching." That is a flexibility which not every religion has.

Doesn't that bother you, too? Don't you find the random nature of the quantum world a little disturbing?
Not at all. I find a reality where not everything is predefined much more comforting because it's an open world. It's much richer. To me, the most convincing indication of the existence of a world independent of us is the randomness of the individual quantum event. It is something that we cannot influence. We have no power over it. There is no way to fully understand it. It just is.

You have said that children should be introduced to quantum phenomena at an early age. Why?
Our brains develop according to the mental activities that we engage in intensely. If you present children with the basics of quantum mechanics, there is opportunity for the development of a different perception of reality. The question is whether we want to take the responsibility of putting somebody, an individual, on a different track than everybody else. Will that person be happy or unhappy in later life?

Do you think you are happier because of your understanding of quantum mechanics?
I am happier, sure. I consider myself very, very privileged to be working on these questions.

+

FROM THE OCTOBER 2006 ISSUE

Discover Interview: Newt Gingrich

The former Speaker—now a leading candidate for the Republican presidential nomination—talked to DISCOVER in 2006 about evolution, stem cells, Washington's two cultures, and why kids should be paid to take science and math.

By Francis Wilkinson | Friday, December 09, 2011

This interview with Newt Gingrich originally ran in the October 2006 issue of DISCOVER. We're re-publishing it now because of its renewed relevance: Gingrich is pegged by many observers as the frontrunner for the Republican nomination for president, after his recent and dramatic surge in national polls.

Newt Gingrich

Gage Skidmore via Flickr

Newt Gingrich hasn't been Speaker of the House for a while. He was chased out of office in November 1998, trailed by a vague but persistent ethical cloud. Depending upon your political views, you most likely recall Gingrich in one of two ways: either as the brilliant revolutionary who overturned a complacent, morally bankrupt Democratic order in the House of Representatives or as the power-hungry backbencher who unleashed the attack dogs of partisanship on the Capitol. Of course, Gingrich is a large enough personality to warrant a bit of both descriptions and then some.

The former Speaker is still entrenched in Washington, D.C., and what he does and says still matters. He is active on the lecture circuit, writes regularly, and has instant access to a wide array of top-tier policymakers. Most are Republican, but lately Gingrich has found common cause on an issue or two with, to use one notable example, Democratic senator Hillary Clinton. It's a pairing that serves them both. Gingrich, too, is rumored to be considering a run for president in 2008. He is well aware of the benefits of a bipartisan stroll down the middle of the road.

Love him or hate him, Gingrich is never dull. In Congress, he was passionate about science and technology in a way that politicians rarely are. And in books like *Winning the Future* (Regnery Publishing, 2005), he has used his great talent for communication to convey not only passion but also new and interesting directions in policy. His influence was once enormous. It may be yet again.

Where did you get your passion for science?

It started as a passion for animals and grew into an interest in paleontology and how life evolved. I began to realize how much science and technology change everything around us. The pure beauty of the natural world and the intellectual elegance of understanding how things work, combined with the power of science and technology to dramatically expand our opportunities, has kept me enthralled.

Who are your guiding lights in science?

The first was Raymond Ditmars, a former curator of reptiles at the Bronx Zoo. I read all his books. I wrote a letter to him when I was about 13; I got a loving note back from the zoo pointing out that Ditmars had died in 1942, the year before I was born.

If you'd gone into science instead of politics, where do you think you would have ended up?

I would have been a naturalist. Edward O. Wilson is probably the closest to my model. I really love paleontology and animals and plants and the complexity of ecosystems.

Do you view evolution as "just a theory" or as the best explanation for how we came to be?

Evolution certainly seems to express the closest understanding we can now have. But it's changing too. The current tree of life is not anything like a 19th-century Darwinian tree. We're learning a lot about how systems evolve and don't evolve. Cockroaches became successful several hundred million years ago and just stopped evolving.

Where do you come down on teaching intelligent design in schools? Do you think the ruling in the Dover, Pennsylvania, case was appropriate?

I believe evolution should be taught as science, and intelligent design should be taught as philosophy. Francis Collins's new book, *The Language of God*, is a fine statement that combines a belief in God with a belief in evolution. I do not know enough about the Dover case to critique the judge's decision, but I am generally cautious about unelected judges establishing community standards—that is the duty of elected officials.

You have called for a dramatic overhaul of math and science education in the United States. What do you propose?

I've advocated, for example, paying kids in 7th through 12th grade the equivalent of what they would make working at McDonald's if they take math and science and get a B or better. Overnight you would change the culture of poor neighborhoods in America. We ought to be honest and say math and science are harder. They're extraordinarily valuable to the country as national security and economic matters. Cultures get what they pay for. We currently pay for rock stars, movie stars, and football and basketball players. Shouldn't being a child prodigy in math be at least as important as being a child prodigy in basketball? Also, I'd allow anyone with substantive knowledge to participate. If you're a retired Ph.D. in physics and you'd like to come in one hour a day to teach physics, I'd let you. No union dues. No credentialing. And I'd argue that if you let everyone in the country who knows physics teach physics, with no credentialing, you'd have a better outcome. Finally, there's no reason to believe that an 1820 school model has any relevance to the 21st century. It's terrific only if you think kids today are going to work in a textile mill. School should mimic reality, not defy it. Almost everyone you know who wants to learn either learns part-time or by immersing themselves for three to five days. They don't go and sit for one hour a day ad nauseam.

You've been quoted as saying, "Those who talk don't know science, and those who know science don't talk."
That's a paraphrase of C. P. Snow's Rede Lecture at Cambridge University, titled "The Two Cultures and the Scientific Revolution," on given in 1959. [DISCOVER co-sponsored a conference on the lecture at its 50th anniversary.] He was making the case that we've had a divergence, where the culture of literature and the culture of science have separated. As a result, if you're a literati you don't know science, and if you're a scientist you can't communicate.

Is that gulf evident on Capitol Hill and in the executive branch?
Yeah, basically. The biggest thing that's evident both in the White House and on Capitol Hill is the lack of a time horizon. The generation that fought the Second World War had fought in the First World War. They had 20 years to think about the Second World War. When they came out of the Second World War, they thought about the cold war. So their sense was, you know, over a 15- or 20-year period we do A, B, C, and D and invest methodically. The founding of the National Science Foundation—all of the things they did up to the early '60s were done with a practical, real-world knowledge of long-term capital development. That's totally missing today. Just as Wall Street has degenerated into an overfocus on quarterly reports, Capitol Hill has an overfocus on this year's budget skirmishes.

In your estimation, what percentage of Washington policymakers, meaning Capitol Hill plus the executive branch, have that longer-term perspective?
Less than one. We are in an enormous mismatch between our governing elite and reality on a bipartisan basis. I'm certain not more than 1 percent of this city has a clue.

You're very active on health-care policy. How are we doing in the fight against cancer?
Cancer can be such a horrifying way to die that there is a very high emotional, moral value to ending cancer as a cause of death. When Andy von Eschenbach, who was head of the National Cancer Institute, stated that he felt we could eliminate cancer as a cause of death by 2015, I was stunned by how Washington totally failed to react. It's a perfect indicator of the failure of the system to do any creative thinking when a man who's a national-class scientist posts that and then we say, "Yeah, what's your next topic?" Or, "How do you feel about the primary in Iowa?" They go right back to the banal because it makes them feel secure.

You've also pressed the health-care industry to go digital.
The Veterans Administration has an electronic health record, and none of its patients lost their records after Katrina. By contrast, an estimated 1,100,000 people with paper records lost all their data. Paper kills. Every American should have a personal electronic health record. You want doctors to take less than 17 years to pick up the latest best practice—which is how long it takes now, according to the Institute of Medicine. You have to go to a whole new model of continuous medical learning, online, pulled forward on demand. And you have to make it available to patients because patients will be the best police of the doctors. The doctors will have to learn to keep up with the patients' questions.

What's the right approach on embryonic stem cell research?
For me it is to say unequivocally that you should not use any stem cells from abortion. On the other hand, there's a lot of research now being done on the ability to take, I think, one out of eight cells from the very earliest stages of reproduction without harming the embryo. If that turns out to be viable, you might end up with people having their own cell line almost as a matter of course 20 years from now.

What about stem cells derived from embryos at fertility clinics?
I think the federal government needs to set an example by making sure that when it is the funding source for such research, it is subject to serious ethical guidelines. I am against human cloning research, and I am against research on aborted fetuses. Having said that, I would not seek to ban research on stem cells in fertility clinics.

You've predicted a fourfold to sevenfold increase in scientific discovery in the next 25 years. What does that mean?
I began thinking of the fact that you have more scientists alive now than in all of previous human history. You have better instrumentation and computation. The scientists are connected by e-mail and cell phone. And they're connected by licensing to venture capital and royalties—and to China and India as reserve centers of production. Put all that together and it leads to dramatically more science than we've ever seen before. And if you get a breakthrough in quantum computing, then you're in a totally different world. My instinct as a historian is that four is probably right. I used that figure when I spoke to the National Academy of Sciences working group on computation and information, and afterwards the head of the group said to me, "That's too small a number." He said it's got to be at least seven. What it means is, if you have a planning committee looking out to 2031, and you're going to have four times as much change, that puts you in the position of someone in 1880 trying to imagine 2006. If you are going to have seven times as much change, that puts you in 1660. And nobody understands that.

Some groups invite you to come talk to them, but it seems that you actively seek out researchers as well.
I follow ideas. When I stepped down as Speaker, I knew I'd been out of sync with science because I'd just been so immersed in politics. I called several people. The president of Georgia Tech was one; I said I just want to come study. I went out to NASA Ames, I went up to MIT. For the first two years, I would schedule time regularly.

Where should we stand on global warming?
I don't think people know, because science has been so involved in politics on this issue that it's very hard to know whom to believe.

Many scientists would say the opposite, that politics has been too involved in science.
I'm just saying it seems to me the data's not nearly as clear as the scientists imply. Let's start with the Gore movie [*An Inconvenient Truth*]. I haven't seen it, but everything I've read suggests he grossly exaggerates the probable dangers. I believe as a matter of prudence it is reasonable to try to lower the carbon load in the atmosphere.

Prudent because we don't understand the science fully, so we should err on the side of caution?
Unlike right-wingers who would say, "Since we don't know 100 percent for sure, we can keep carbon loading," I'd say there is enough evidence that it's reasonable to try to move toward renewables, to try to move toward

conservation, to try to move toward a hydrogen economy. All those are reasonable steps. But none leads me to panic. We are dramatically cooler than we have been for large parts of Earth's history. We could do everything mandated by Kyoto [the Kyoto accord on climate change] times 10, and if the sun changes its behavior, it'll just swamp us. There's a certain human egocentrism that undervalues how big the system is.

Isn't a hydrogen economy still pretty far off?
I've been actively involved with the "25 by 25" group that says we ought to be using 25 percent renewables by 2025.

How do you see that happening?
I am a [Theodore] Rooseveltian Republican. I believe in incentives, not punishment. I'd change the market and let the technologies sort themselves out. But I will also say I'd look at soy diesel, at E85 ethanol, solar power, wind power, and better systems of conservation. I could also argue that you want to move toward fuel-cell hydrogen models as rapidly as you can figure them out. And if you can build a very stable next-generation nuclear power plant, then we have to look at a substantial amount of nuclear as part of this process.

You've said that humans have a destiny to spread across the solar system and the cosmos. How do we accomplish that?
Twenty-five years ago I said we have to start talking about how the moon will be governed. I suggested it ought to be governed by free people in a free system obeying the rule of law. People thought it was kind of wacky, but we were trying to make a point. You have NASA, this huge, graying bureaucracy that sits around wasting money and enforcing timidity. Just look at the length of time between shuttle launches: If the Wright brothers had done that, we wouldn't be flying today. You have to have a risk-oriented, high-tempo, entrepreneurial model; you ought to offer enormous rewards for lowering the cost of getting into space. You want everybody and their brother to show up and compete. NASA's been a success. I voted for it, I supported it, but I have to say it has been a bureaucratic nightmare.

If you were president, what would you do to advance the interests of science?
The first thing you do is you talk about it every day. You talk about why investing over here is going to help cure cancer. You talk about investing in new forms of learning to allow young Americans to break out. You ought to talk about what we could get done in space in the next 20 years if we had an entrepreneurial spirit. What makes science fun is this adventure of discovery, which is both aesthetically pleasing and is productive in a practical way. We need to get back to being that kind of system. And that requires real leadership at the top because the underlying biases of this culture are commercial rather than scientific. It should be as possible, or more possible, to succeed in America as a scientist or engineer as it is to succeed as a rock star, athlete, or movie star. Unless you set that goal—and that's got to be a culturally defined goal, the rewards system has to be built in—we will not sustain our leadership role in the world.

FROM THE APRIL 2012 ISSUE

Discover Interview: The World's Most Celebrated Virus Hunter, Ian Lipkin

The Columbia University researcher describes his quest for HIV in San Francisco and SARS in China, the immune cascades that may cause autism, and the infectious roots of psychiatric disease.

By Grant Delin | Friday, May 11, 2012

RELATED TAGS: INFECTIOUS DISEASES, GENES & HEALTH, VACCINES, MENTAL HEALTH

Photograph by Grant Delin

When Ian Lipkin chose a career in infectious diseases, he envisioned hunting for pathogens in daring treks around the world. Though disappointed to learn that modern-day virus hunters work largely from the lab, he still wound up a pioneer. At the Scripps Research Institute in La Jolla, then at the University of California, Irvine, and since 2001 as director of the Center for Infection and Immunity at Columbia University's Mailman School of Public Health, Lipkin has developed groundbreaking techniques that have helped a new generation of disease detectives sleuth out the infectious roots of mystery ills, chronic disease, and neuropsychiatric disorders like autism and OCD. Lipkin's signature invention is a technology called Mass Tag PCR, which searches through large numbers of known viral and bacterial genomes to identify a culprit in a few hours. He often complements this test with others, including microbial detection microchips (GreeneChips) and gene sequencers that can complete an exhaustive search for known and unknown pathogens within a tissue sample in less than a day.

When DISCOVER features editor Pamela Weintraub interviewed Lipkin last year, he had to cut his workday short because his dog, Koprowski—a gift from Polish virologist Hilary Koprowski—was desperately sick. Lipkin had a treatment plan: not an antiviral drug or chemotherapy, but red meat. “It has antibiotics, it has growth hormone, it has everything. Koprowski’s my best friend in the world,” he explained before descending into the subway and heading home.

You were in the first class of men at Sarah Lawrence, where you studied anthropology, even shamanism. Yet you are known for hunting pathogens. How did that come about?
I felt that if I went straight into cultural anthropology after college I’d be a parasite. I’d go someplace, take information about myths and ritual, and have nothing to offer. So I decided to become a medical anthropologist and try to bring back traditional medicines. Suddenly I found myself in medical school.

But you didn’t become a medical anthropologist. Instead you studied neurological disease and infection. Why?
By 1977 I had gotten a fellowship at the Institute for Neurology in London, where a professor named John Newsom-Davis was working on myasthenia gravis, a neuromuscular disorder characterized by weakness often so profound that people lose their ability to breathe. Back then, nobody really understood what the disorder was. John was trying something new, treating it with plasmapheresis.

What is plasmapheresis, and why did Davis think it would help his patients?
Plasmapheresis is a method where you take the blood, put it into a centrifuge, and as you spin it the components separate out. You have white cells and platelets in one area, red cells in another. And then you have plasma, which contains antibodies. You introduce what amounts to a straw to suck up the plasma. You replace plasma with albumin to maintain the blood volume, but now the antibodies are gone. With the antibodies gone, the symptoms are relieved.

With antibodies at the root of symptoms, you knew that a pathogen could be the precipitating cause. How did you end up linking infection and diseases of the nervous system and brain?

It was the apex of freedom and joy in the gay community, but we soon started seeing HIV.”

I took a residency in neuroscience at the University of California, San Francisco (UCSF). It was 1981 when I drove into San Francisco on Gay Pride Day in a Ryder truck right up Castro Street. It was the apex of freedom and joy in the gay community, but we soon started seeing HIV, and I was one of the only people willing to see the patients who were both sick and had neurological disease. My clinic took anybody who had gay-related immunodeficiency, or GRID—an early name for AIDS. One thing I found that was interesting and important was that a lot of people with grid had idiopathic thrombocytopenic purpura, a bleeding disorder. It’s idiopathic, meaning nobody knows what causes it. Thrombocytopenia means you don’t have platelets, so the blood doesn’t clot properly. Purpura refers to the fact that you get these blotches on your skin where blood vessels break. Their platelets were getting chewed up by their antibodies.

+

HIV was turning the patients' bodies against themselves, the hallmark of an autoimmune disease. But you found that their immune systems were attacking not just their blood but their nervous systems as well. How did that finding come about?

I discovered this because we then had the only MRI scanner in the world at UCSF. As a result, a colleague asked me to see a patient of his, a ski instructor from Vail, Colorado. The man was thought to have MS, multiple sclerosis. So this fellow arrived at my clinic early one morning, and I did a very detailed neurological exam. As I left him and came back to him over the course of an hour, his symptoms changed. He was becoming quite fatigued, because the testing is arduous. So I gave him a break of 15 minutes. And he came back in to see me and now both sides of his face were so weak he couldn't smile. He had numbness and tingling and then, right there in my office, his face became so weak he couldn't close one eye. Then he couldn't close the other eye.

It was clear this wasn't MS, and I thought of a couple of causes for what I saw. One was exposure to some kind of toxin. So I checked the man's spinal fluid for the presence of protein indicating inflammation. His protein was orders of magnitude higher than anything I'd ever seen, and the spinal fluid came out like glue. My colleagues asked what I wanted to do, and I said, I want to do plasmapheresis.

Why did you go back to that technique? Because you wanted to remove the antibodies that you felt were driving his symptoms?

That way I wouldn't be adding a drug that I couldn't remove. I'm just reducing the number of antibodies that might be causing this disease. So I talked with the renal dialysis people who had the machinery required to do this, and they said, this guy's gay, so he has this GRID, right? And he has elevated liver enzymes, so he possibly has non-A, non-B hepatitis. And you want us to contaminate our machines with this guy's blood? I don't think so.

What did you do then? I know you couldn't abandon him.

I'd heard about a Russian guy with a centrifuge at Pacific Medical Center on the other side of town. He was willing to help me, provided two things: Number one, I would take responsibility for inserting the needles in my patient's arm. And two, he would be paid in cash—$600 up front for every treatment. So I put my guy in my Ford Fiesta, and I drove him over to this medical center. He could barely walk, so I walked him in. He lay down on this hospital bed, and I put in two large-bore needles, one in each arm.

After the first treatment he modestly improved—and he was better yet after the second treatment. I treated him on and off for two years. He started skiing again but eventually progressed to AIDS and died. While he was getting this treatment, though, it helped him function. After that I decided to study infectious disease.

San Francisco in the early 1980s—that would have been a logical time to continue your study of AIDS. But that's not what happened.

I flew down to the Scripps Research Institute in La Jolla to meet with neuroimmunologist Michael Oldstone. I told him I had all these nerves from AIDS patients and all this brain material. But he says to me, AIDS is a flash in the pan. There's a vaccine around the corner. You're going to work on the Rosetta stone of immunobiology: lymphocytic choriomeningitis virus, or LCMV.

So you ended up going to work at Scripps. Why did Oldstone think that virus was so important, more so even than HIV?

Oldstone was interested in infections that can persist and cause damage to the greater organism but not the individual cell. LCMV, a cause of meningitis in humans, shuts down the ability of the pituitary gland to make growth hormone. The virus doesn't kill the cell, but it suppresses transcription and translation of genes, so the organism as a whole suffers but the individual cell looks OK. My contribution was showing that there were specific effects on neurotransmitters linked to the behavioral manifestations of the disease. This became a model for understanding how persistent viral infections affect the central nervous system. Oldstone gave me an opportunity with LCMV, but he was a tough guy.

In your next project you tracked down a virus that caused both physical and behavioral changes in animals. What happened there?

I was at a meeting in 1986 when Kathy Carbone and Bill Narayan, both from the Johns Hopkins School of Medicine, were presenting their work on Borna disease, a neurological syndrome in some mammals and some birds. They'd been working with rats and had two models for what they said was an infectious disease. One model included an adult infected rat and a neonatally infected rat. The adults had profound inflammation in the brain and movement disorders. Some were massively obese, and many of them died. The neonatally infected rats were smaller than normal rats and more hyperactive, but they didn't die and they didn't have movement disorders. And the researchers were like, really? How could the presentation of the disease be so different in neonates and adults?

Were you able to solve the mystery of Borna disease?

After my work with LCMV, I knew how to measure neurotransmitter levels. So I did my measurements, and I could see what was different in the adult versus the neonatally infected animals. But I became intrigued by the fact that Bill and several very good people were trying to identify this virus responsible for Borna and couldn't find it. Oldstone didn't have the necessary equipment, so he recommended that I talk to other people at Scripps. There was a guy there, Michael Wilson, whose strategy was eliminating as much irrelevant material as possible from a sample until only the virus was left.

So you just kept eliminating until you found your virus?

It took me more than two years to get the Borna system up and going. First I had to get brain material from an infected rat. Then I had to get permission to infect living rats with this bug because it's potentially dangerous, and the USDA was not excited about testing an agent that can kill horses and sheep that's not native to the United States. By now it's 1987. I injected healthy rats with brain material from infected animals, then I waited until the rats developed disease. I removed the brains of the rats, cut them in half and studied one half microscopically. If a rat brain showed inflammation, I assumed the animal had Borna disease. And I took the opposite half of the brain, pulled out the hippocampus, which is the area described by researchers as the target for disease, and ground it up, saving the RNA . Eventually I succeeded in making a library of genetic material—single-stranded RNA —from the hippocampus of an infected animal. I labeled the RNA with radioactive markers so it was "hot." Then I made another library of RNA from the cerebellum of a normal animal, and this wasn't hot. I put the RNA from both samples in a tube and mechanically shook it for three days behind plastic shields made from discarded Jack in the Box restaurant signs, because they were free and excellent at blocking radiation.

In essence, most of the material from the rat brain bound together, separating out and leaving viral molecules behind. Is that right?
I wound up with a mixture of double-stranded material [because some of the single strands of rat RNA bound together to form a double helix]. The double strands represented material from the rat brain: either the Borna-disease brain, the normal brain, or a combination of the two. I also got single-stranded material—hot material from the Borna brain alone and cold material from the normal brain. All the single-stranded material got separated out on top of a filter, but only the hot Borna brain material appears on film. [Radioactivity exposes photographic film.]

So the hot single-stranded material, which did not bind to the brain tissue in your mixture—was that the Borna virus?
Not yet. I had to eliminate more. Now I take the spleen and I take lymph nodes and I take thymus from normal rats and I grind them all up because, theoretically, these organs contain all the transcripts that might represent inflammatory proteins like chemokines and cytokines. Everything hybridized until I was left with just a 38-kilobase protein and a 24-kilobase protein representing viral DNA. I still didn't have the virus, but I had protein associated with the virus.

You needed many more complex steps, far too elaborate to explain here, to isolate the viral genome and then the virus itself. But when you were done, you had reinvented the field of pathogen discovery with your molecular techniques.
Of all the things I've ever done, I am most proud of that. If the Borna virus had been proved to cause a significant human disease, it would have been an even bigger deal.

Why do you say it's not significant? The Borna virus has been implicated in many different diseases.
A group in Berlin reported Borna in AIDS. A Japanese group reported it in chronic fatigue syndrome at very high levels. People were reporting it in brain tumors, in Alzheimer's disease, in multiple sclerosis. But we could never replicate the findings. Our new blinded, case-controlled study, published in Molecular Psychiatry, finds no association between Borna disease virus and psychiatric disease. People were contaminating tissue cultures. People were contaminating molecular assays.

So after all that, Borna does not cause any human disease at all?
I've seen no evidence of it, and we have not been able to demonstrate Borna virus infection in psychiatric patients or chronic fatigue syndrome patients. Having said that, we have recently shown that Borna virus sequences are integrated into the human genome and have been there for hundreds of thousands of years. Which means that at some point people have been infected with Borna virus. But whether they can currently be infected with it and whether it can be linked in a cause-and-effect relationship with disease are completely separate issues.

Your next big conquest involved a much more famous pathogen. You identified the West Nile virus after the first big U.S. outbreak in New York City in 1999. How did you get involved in that effort?
By August of 1999 I'm doing research in emerging diseases at the University of California, Irvine, and I'm invited to a meeting in Albany, New York, where we learned about an outbreak of what the Centers for Disease Control and Prevention [CDC] said was St. Louis encephalitis virus [SLE]. One investigator noted something

unusual in people who had encephalitis that summer: Though otherwise healthy, they became especially weak and even required ventilators. Another noticed that crows were dying, along with a lot of animals in the Bronx Zoo. The CDC said, we don't want to be bothered by these birds, and these other things are not relevant. We're trying to address this SLE. But no one could isolate the agent. Then the CDC sent us the samples, and in 48 hours we knew that it was not SLE, and it was growing in the brain. We found material from the brain that matched the flavivirus family, to which West Nile belongs. Then we sequenced the genome. We were the first to clone an entire genome out of degraded human material. We reported West Nile virus in human spinal fluid and blood.

You moved your lab from Irvine to Columbia University in New York City around the time of 9/11. It must have been an extraordinary time for a pathogen hunter. There were the anthrax attacks and the global panic over severe acute respiratory syndrome, or SARS.
SARS was the first plague of the 21st century. In the winter of 2002 we began hearing chatter that there was a new respiratory disease in southern China. Most people thought it was probably some variant of flu, but then we found it was a coronavirus, so called because it's spherical with a little crown [corona in Latin] composed of spikes of protein. It was a surprise because coronaviruses aren't typically associated with human disease. We found we could grow the virus in certain cell types, and I began trying to develop a rapid molecular test, but it turned out not to be very sensitive. So we obtained some information about the virus's genetic sequence and developed a real-time PCR assay [using a technique that rapidly replicates a stretch of DNA] that was 50 to 100 times more sensitive.

Chinese public health officials must have been interested in that.
The Chinese consulate invited me to a magnificent banquet at an East Side Chinese restaurant in New York. Halfway through the meal they said to me, we need you to go to Beijing tonight. People were dying there. It was the middle of an outbreak. And there was no treatment. I said, well, I can't go by myself. So I convinced Thomas Briese, my colleague at Columbia, to come along. The morning we flew out, my kid is crying. Thomas's wife is crying. I'm traveling with a suitcase filled with booties, gloves, masks, and 10,000 test kits for SARS. Nobody was going into Beijing because people were dying there. There were only three people on the final leg of the flight—Thomas, me, and Elisabeth Rosenthal from The New York Times. She was picking up her kid.

What happened when you arrived?
Chen Zhu, now China's minister of health, was waiting at the airport with a red carpet. The streets were deserted. Tiananmen Square was empty. The Forbidden City was empty. The next morning we went to the Great Hall, and I'm told I am there to design their SARS program. There were 250 people waiting to hear what I wanted them to do.

Eventually they did manage to obliterate SARS in China.
SARS was contained not because of a drug or vaccine but because we identified people who were infected or at risk, and we isolated them. When I went back to see Chen Zhu, he was in a hospital with an unexplained liver problem. At the nursing station they didn't even have soap. The first thing I did was sit down with him, and I said, you must do two things for me. There can be no spitting on the sidewalks because this spreads all these germs. And doctors and nurses coming to see you must wash their hands. By the time I left his room half an hour later, there was a prohibition against spitting on sidewalks and there was soap and water and paper towels in hospitals.

Your newest research looks at a particularly insidious set of chronic diseases that can result from infection in the womb. These diseases can produce lifelong psychiatric effects. How does that work?

The connection between prenatal infection and damage to the fetus has long been known. Exposure to syphilis, at its most extreme, results in stillbirth. Prenatal exposure to infections could result in microcephaly [a neurodevelopmental disorder in which the circumference of the head is smaller than normal]. But if the damage is more subtle, subtle changes in behavior can result. The child is still breathing, the child is walking, the locomotor function is not so abnormal that it's incompatible with life in our culture. There was a time when these children would have died in utero, but now they survive, and you see some of these abnormalities come to the fore.

Have we reached the point where we can link specific infections to specific psychiatric disorders?

No, the connection is much more complex. When I worked with LCMV, it became clear that any sort of perturbation could damage the nervous system. Nerves find their way to specific locations through signposts that are part of the immune system. And if you increase immunological molecules of certain types, a nerve may jog this way as opposed to the way it's supposed to go. It may not make a difference what the infectious agent is—bacterial, viral, or parasitic.

If the identity of the infection isn't critical, what is?

The important things are the genetic background of the individual and the timing of the insult. If you look at the original work on the epidemiology of thalidomide [a morning-sickness drug that turned out to cause birth defects], there were specific time points where, if the woman was exposed, the baby had a high probability of having bona fide autism.

One of the most fascinating links between infection and mental disease concerns PANDAS, pediatric autoimmune neuropsychiatric disorders. The bottom line is that strep might cause obsessive-compulsive disorder. How could that happen?

An infection like strep throat provokes an antibody response, but the antibody created to fight the strep also recognizes proteins that are part of your body. Antibodies don't typically traffic much in the central nervous system. But if you have any one of a number of other infections or an insult like head trauma, the blood-brain barrier [which normally protects the brain from pathogens] opens transiently. Depending on how long and where the opening is, the antibodies get access to part of the central nervous system or brain. We are studying this process now in mice, using drugs to open up a portion of the hindbrain or the forebrain or the hippocampus and tracking the effect.

Could autism be another version of a PANDAS-like disease?

It's possible, in some people. There is probably a group of people who have a genetic component to autism, and for them, there may not be much of a trigger or any trigger at all required. Another group is genetically predisposed, and if they encounter some factor or factors, individually or in combination, it could result in either the onset or the aggravation of the neurodevelopmental disorder; by factors, I include everything from heavy metals to infection. And lastly, there is a group that may be relatively or entirely normal but is exposed prenatally to some factor or factors that have an effect on their nervous system and that manifests as autism. This is the hypothesis, at least.

+

You are trying to put all this research together through a prospective study called the Norwegian Autism Birth Cohort. What's that about?

The idea is that you can get only so far by examining people when they're sick, because the seeds of illness may be laid many years before. In a prospective cohort, you can follow children from before birth in an unbiased way, collecting information and samples and maybe making associations between factors and outcomes after the fact. We're going back as far as we can, which is the first prenatal visit at roughly 17 weeks' gestation. And the study is being done in Norway because there's universal health care; you don't have to be concerned about discrimination for insurance purposes based on disease, and as people get ill, you have long-term follow-up.

What could that study tell you about the nature of autism?

We have thousands of biological samples that will be transferred back here to New York, and we're going to analyze them using all the tools of microbiological analysis we developed to look at acute diseases in the past. Because we have blood samples that are obtained from the mother during the course of pregnancy and at the time of birth, we can examine a whole range of proteins and messenger RNA s that may be reflective of genetic defects or exposures. We may not detect an autism-causing agent specifically, but we will see that there is a marked increase in specific biomarkers. This allows us to define in a very broad sense what proteins, nucleic acids, pathogens, and toxins might be part of the milieu of the fetus.

How would you describe your overall approach to pathogen discovery?

In microbe hunting we start with the result, the disease, and work backward, examining the paths and pathogens that might have led there. Finding footprints of a microbe—whether you're seeing antibodies or the virus itself—is just the beginning of solving the crime. Initially the evidence is circumstantial. Like in criminology: Seeing a suspect on the street corner where somebody was killed is not enough. We still need motive and opportunity. Motive is tropism [seeking nutrients or energy] and virulence [ability to multiply and cause disease]. Some microbes are known to infect the lungs or the intestines or the brain. Finding them in a typical location gives us confidence we are on the right track. Opportunity—could it have done the damage? Some infectious diseases are seasonal. Mosquito-borne diseases, for example, are common in the summer but rare in the winter. Noroviruses are common on cruises. That's where biological plausibility comes in.

You sound a lot like an old Hollywood detective.

If you can find a smoking gun, if you can show that this preceded that and somebody's been shot in the past, then you can get a conviction. That's exactly what it's like.

FROM THE MAY 2012 ISSUE

Discover Interview: Jaak Panksepp Pinned Down Humanity's 7 Primal Emotions

He tickled rats and showed that making them laugh is serious business.

By Pamela Weintraub | Thursday, May 31, 2012

RELATED TAGS: MEMORY, EMOTIONS, & DECISIONS, MENTAL HEALTH, DRUGS & ADDICTION

Jaak Panksepp communes with the rats in his lab on campus.

Photograph by Greg Ruffing

Jaak Panksepp has taken on many unusual roles in his storied career, but none so memorable as rat tickler: He learned how to stimulate the animals to elicit high-frequency chirps that he identified as laughter. Panksepp's interspecies game-playing garnered amused media coverage, but the news also stirred up old controversies about human and animal emotions. Since the 1960s, first at Bowling Green State University and later at Washington State University, Panksepp has charted seven networks of emotion in the brain: SEEKING, RAGE, FEAR, LUST, CARE, PANIC/GRIEF, and PLAY. He spells them in all caps because they are so fundamental, he says, that they have similar functions across species, from people to cats to, yes, rats.

Panksepp's work has led him to conclude that basic emotion emerges not from the cerebral cortex, associated with complex thought in humans, but from deep, ancient brain structures, including the amygdala and the hypothalamus. Those findings may show how talk therapy can filter down from the cortex to alter the recesses of the mind. But Panksepp says his real goal is pushing cures up from below. His first therapeutic effort will use deep brain stimulation in the ancient neural networks he has charted to counteract depression. Panksepp recently sat down with DISCOVER executive editor Pamela Weintraub at the magazine's offices in New York City to explain his iconoclastic take on emotion. His new book, *The Archaeology of Mind: Neuroevolutionary Origins of Human Emotion*, will be published in July.

Your interest in emotion was sparked by an odd job you had in college. What happened there?
Putting myself through college at the University of Pittsburgh in 1964, I did night work on the side and ended up a night orderly in the psychiatric hospital. I came in when it was dark and people were starting to settle down and go to bed. Some of them were on heavy meds. Others were very disturbed and would wander all night unless they were put into restraints. Everyone who worked there had free access to the patient files, which were thorough in relating the life history of individuals. You really got to know a lot about the people. After that I decided to get into the field.

How did you get started in those early years?
I went to do my Ph.D. at the University of Massachusetts, starting in the clinical program. In my first year, I had the great fortune of becoming a Veterans Administration trainee and got a job in the electroencephalography (EEG) lab where they analyzed brain waves, mostly to diagnose seizure patients. The head of the lab was a psychologist, Arnold Trehub, who pretty much asked me, what do you want to do with your life? And I said, what I'm really interested in is brain stimulation and reward.

That was a rather precise and arcane interest for a clinical-psychologist-in-training during the 1960s. How did the idea occur to you?
A new faculty member at UMass, Jay Trowill, was interested in this exciting new technique: inserting electrodes in rat brains to create pleasure or excitement. After you inserted the electrode, you gave the rat the chance to turn it on or off itself by pushing a lever. Thanks to my experience in the EEG lab, Jay asked me to be his first student and run his lab. I had to build my own boxes that had levers that animals would press to turn on the electricity.

What happened when you dropped a rat in one of those boxes you built?
He fell on the lever, causing the electrode to stimulate his medial forebrain bundle, a reward center. And he worked and he worked and he worked for hours. I didn't have to train the animal. I just dropped him on the lever, he got one taste and he started hitting it.


Jaak Panksepp behind the *BG Thinker* at Bowling Green State University.

Photograph by Greg Ruffing

Those kinds of reward experiments had already been going on for years before you got to them. What insights did you add?
I observed that whenever the animal pushed the lever and got the motivating jolt, it explored its world energetically. That was very different than anything that happened when animals were working for food rewards, where they always stopped when they were full. To get at the difference between the two types of rewards, I designed an experiment that injected sugar water into the rats' stomachs whenever they pushed the stimulating lever. I put one animal in the apparatus and went out to get lunch. When I came back it had killed itself with too much sugar. It just kept pumping more and more until it went into osmotic shock. The next time I didn't walk away.

So even with a belly full of sugar, the rat was still craving something. What was going on?
I tried to answer that fundamental question through the behavior of my lab rats. It was clear that when I stimulated the reward center in the medial forebrain, they were not engaged in the kind of relaxation they felt when they stopped to eat or drink. It was just the opposite. It was the kind of behavior the animal showed when it was looking for food. So I started thinking in those terms: This was mother nature's way of allowing animals to explore the world. It was an exploratory system; it was about generating expectancies, seeking rewards.

You were describing a rat's experiences in terms usually associated with human experiences. That wasn't really the style of the times, was it?
I brought up the psychological issues, and my professor said, Panksepp, I've seen guys like you before, and they're not around anymore. Psychology was not on the table for animal research people. It's all just behavior, he told me. I said, well, I guess I'm not supposed to think here. This is like some kind of religion. You've got a certain view and you'd better say the mantra because that's how they're training you, and believe me, young scholars were brainwashed by the hordes. Most of them were ready for the brainwashing like sheep going to slaughter.

So how did you resist the academic brainwashing?
I learned to bite my tongue until they couldn't hurt me any more. I bit my tongue many times, but not hard enough usually. So gradually I became a radical without wishing to be a radical.

What were the radical ideas that motivated you? My major question was, what are emotions?
Since we could turn on the emotions with electrical stimulation, for my dissertation I decided to study rats for the anger and rage system already documented in cats. You could turn a peaceful pussycat into a raging monster by stimulating specific parts of the hypothalamus. It was much harder to turn lab rats rageful, because cats brought in from the street were predators. A predator needs that kind of attack system, whereas an omnivore like a rat needs a searching system.

Did you eventually find the rage system in rats?
Yes, rats have this system in much the same areas of the brain as cats. Once I obtained aggressive behaviors in rats by stimulating specific areas of the brain, I started asking whether they liked or disliked the feelings by having them press a lever to turn the stimulation on or off. The answer depended on the kind of aggression I induced. Whenever aggression was predatory, marked by stalking and quiet biting attack, rats turned on the brain stimulation over and over again. I realized this predatory attack came from the seeking system. But whenever the aggression was agitated, resembling human anger, rats would press levers to escape the artificially aroused rage feelings. Anatomically and psychologically the two types of aggression were very different. More broadly, feelings of seeking, lust, care, and play feel good. Rage, fear, and panic feel bad.

+

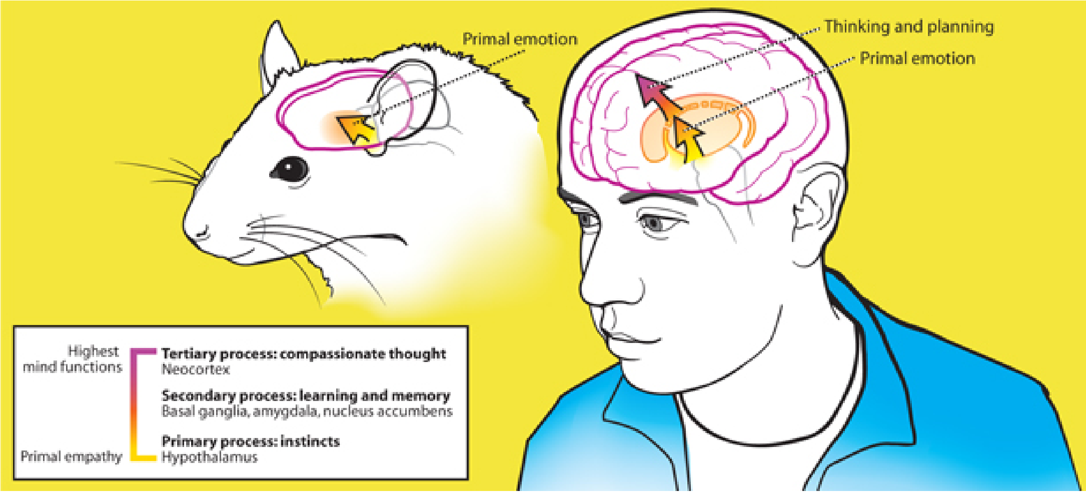


Illustration by Elisabeth Roen Kelly

You defined seven fundamental emotions, all spelled with capital letters in your academic papers. Why?

These are the emotional primes, the primary-process emotional systems associated with specific brain networks and specifically designated in the brain-stimulation studies of emotions. They are seeking, RAGE, FEAR, LUST. CARE, PANIC/GRIEF,and PLAY. These are capitalized because the evidence supports a category of evolutionarily homologous experiences, equivalent across different species of mammals.

In your next career move, you wound up at Bowling Green State University in Ohio in 1972. Why there?

It had a unique lab run by someone I found totally fascinating: John Paul Scott, a biologist in the psychology department who had done more work than anyone else on social attachments in dogs. Attachment is the bond of selective preference between a mother and a child, whatever the species. Mother dogs and their pups bond, mother sheep and their lambs bond, and so forth. When a real bond has been established, the young selectively prefer their own mother, and follow her around persistently in order to feel comfortable. Conversely, the mother will shower all her devotion on just her own babies. When this attachment bond is broken, the young cry and cry until reunited with the mother; this is the panic system in action. Animals that grow up crying the most because they are separated from their mothers for the longest are generally maladjusted. Scott insisted that attachment had to be studied biologically, but no one knew how.

Then you found a way to study attachment. How did you do it?

Serendipitously, that was the moment, in 1973, that scientists discovered the opiate receptor—the first neurochemical receptor in the brain. The day I heard that, I said, this has got to be the attachment mechanism. Opiate addiction is another phenomenon that creates a powerful bond. We call it by a different name, addiction, but it is activated via a molecule that produces good feelings, and mom produces a lot of good feelings in the young ones, too. They feel comfortable, they feel soothed, and opioids have that same property, psychologically.

How could you test the idea that social attachment is related to chemical addiction?

I had the insight that if you wanted to understand attachment, you would have to study crying. My first successful experiments used dogs. We took young pups and gave them morphine. Then we removed them from their mothers. The more morphine they got, the less they cried and the quieter they were. They sat alone and were satisfied, as if the mother was right there. Significantly, we could comfort the animals only with opiates like morphine, not with the types of agents often used to quell anxiety, the benzodiazepines. So we knew the crying wasn't a physical fear. As with aggression, there were two kinds of anxiety systems. One was fear that a predator would attack, and the other was panic over separation.

What was the response to your discovery?

We had to use emotional language to describe what we found, and the bottom line is we simply got rejected as being crazy. For the next 10 years, all we heard was, you're just sedating animals, what the hell? We don't have to pay attention to you. So we didn't get a penny for that work. When you don't have a penny to pursue research, that's a very expensive canine laboratory. After John Paul Scott retired, I was given the job of saving the canine research facility. We must have written at least half a dozen grant proposals, and the message was clear: We're not gonna get funded no matter what we do. Dogs were the perfect species for the study of social attachment, but no one got it. The best canine behavioral research laboratory, and the last one in the country, died with me. I was incredibly disappointed.

So what then—you turned back to rats?

No, because rats don't cry. They give a distress call, but it's not about social separation; it's just, I'm cold, I'm out of the nest. But the guinea pig showed real vocalizations, and we found, yes, they also quiet down with opiates just like dogs. So Barbara Herman, one of my first Ph.D. students, took on the project of mapping the crying system in the brain of guinea pigs. That system converged in the periaqueductal gray area, an ancient area of the brain. By putting electrodes there, you could get the animals to make very intense separation calls. The calls continued as you put electrodes into the medial thalamus and the basal ganglia, areas seen as part of an anxiety system by fear researchers. I kept saying, this isn't fear, this is a different anxiety. They didn't care to listen because they never even thought about the separation call. But we mapped the anatomy. By 1978 we had mapped the attachment system in three species in all.

Today the bonding hormone is thought to be oxytocin, a chemical secreted after intense social experiences such as birth and sex. Is that an attachment molecule, too?

We studied oxytocin, and it turned out to be as powerful as the opiates in reducing separation distress. Every process in the brain has multiple chemistries. The three that had enormous effects on attachment were the opioids; oxytocin, which was superbly effective but had to be put directly into the brain because it does not cross the blood-brain barrier; and prolactin, the stuff that manufactures milk.

Then you made a U-turn: Instead of studying separation anxiety, you started to study play and laughter. Why?

It was the classic masks of theater, sadness and happiness. We had essentially done the work on the sadness mask. I wanted to move to the joy mask. Joy is social, so you're looking at play. Play is a brain process that feels good, that allows the animal to engage fully with another animal. And if you understand the joy of play, I think you have the foundation of the nature of joy in general. Part of its benefit is simply taking away the psychological pain of separation. Play is engaging in an attachment-like way with strangers, which you have to do later in life.

Time for another animal experiment, right?

To study attachment, we couldn't use rats or mice. They're laboratory animals bred inadvertently to live by themselves. But I noticed that rats in the lab are wonderful for play. Psychic pain reduces the inclination to p

—but since rats don't feel it, they can be separated without panic and then when you put them together, bang! They play.

And the rats played with you, too?
After the experiments we'd dim the lights to make the rats more comfortable. That was our time to have fun. You see me sitting there and saying, come on, guys, come on—it's okay. I knew that if I could tickle them, they would get jazzed up more, and that's what happened, right in front of the camera.

How did you turn that kind of playing around into a rigorous experiment?
I thought about the hunger research I'd done in the past. If I wanted animals to eat, then the best way was to make sure they hadn't eaten for a while. If I want animals to play, I'd have to make them hungry for play. So I put them in a cage alone, apart from their family, first for 4 hours, then 8 hours, then 12 hours, and finally 24 hours. I was looking for a behavior that I could use to measure play, like jumping on each other. How often do they bounce and touch each other? Then they run around—it's too complex to follow unless you do slow-motion movies—and they end up wrestling. These behaviors were very easy to measure. We collected a lot of data on the response to social hunger.

Is play embedded deeply in the brain, the way attachment is?
Many experiments over the years suggested it was, but to be sure I removed the upper brain of the animals at three days of age. Amazingly, the rats still played in a fundamentally normal way. That meant play was a primitive process. We saw, too, that play helped the animals become socially sophisticated in the cortex. That's why it's so important to give our kids opportunities for play.

And yet it seems that childhood play has become much more controlled than it was when I was young. I have gone to ADHD meetings to consider this childhood problem. But the doctors do not want to hear the possibility that these kids are hyper-playful because they're starved for real play—because they are giving them anti-play medicines. Teachers are promoting the pipeline of prescription controls as much as any other group, because their lives are hard. They are supposed to be teaching kids at the cortical level of reading, writing, and arithmetic, but if they've got kids who are still hungry for play, it's gonna be classroom chaos. And you can sympathize with them, because they should be getting kids that are sufficiently well regulated to sit and use their upper brains. But the kids' lower brains are still demanding attention.

What happens to animals if they are deprived of play over the long term?
They look normal and they eat normally, they're just not as socially sophisticated. Animals deprived of play are more liable to get into a serious fight. Play teaches them what they can do to other animals and still remain within the zone of positive relationships. If you have play you become sociosexually more sophisticated. Let's say you have the classic triangle: two males and one female, because males are competitive for sex. So if you've got one animal that's had lots of play and the other animal hasn't, guess who is successful? The animal that's had play knows how to stay between the female and the other male. The other guy's a klutz.

Did you ever find a way to track and measure the play response in rats?
Yes. I had a postdoctoral student, Brian Knutson, who asked me whether there was a play vocalization. I said, we know they don't make any audible sounds but maybe there's ultrasonics. We wound up buying the equipment so his study could be done. Brian came in the first day after it was set up and said, Jaak, there is a

sound when the animals are playing. That was the 50-kilohertz chirp [at a pitch far above the range of human hearing].

What does the rat chirp mean?
We found it was most common in positive social situations—sexual, maternal, and play. They're all in the 50-kilohertz range, but there are many subtypes. Animals start showing anticipatory chirps before access to play. They also chirp in anticipation of food. After Brian left, I woke up one morning—it must have been 1996—and I said, what if that sound is laughter? I got another student, Jeff Burgdorf, to work in the lab. Every morning I would get in at 9 a.m. He would be waiting for me, and I would say, Jeff, let's go tickle some rats. I tickled the first rat and it worked beautifully, and the second, and the third. Eventually we developed a standard method where we were doing everything the same and then studying the 50-kilohertz chirps.

Isn't that making the experimenter part of the experiment?
Yes, but you can't tickle without it. We tried to get tickle machines—they were nothing like the human hand. Tickling has to be done in a joyful way. It has to have the characteristics of play, and since I had been immersed in play, I didn't see that that was a big problem. The first animal worked and every animal worked. We got totally addicted to this. Give an animal a really good time, you know? They become so fond of you, it's unbelievable.

But do the rats recognize you?
Oh, of course. The tickle is a way to the social bond in the rat—a friendship bond. That's part of the function of play. So we have a psychobiology of cross-species friendship.

Does it cut both ways? Do the rats get mad if you do something wrong?
At one point we decided to ask, what happens to the rats when you put your hand in there but no longer tickle them? Our experiment was to have one hand deliver a tickle touch, and another, just a petting touch. The animals preferred the tickle hand enormously. When the animals came to my petting hand, I got my first bite ever. But it didn't hurt; it must have been a play bite, like a puppy bite. Then we started measuring play bites. The more the animal wanted to play, the more it would nip, never breaking the skin. I said, whoa. This behavior is totally understandable for anyone who has a cat or dog: Rats give play bites that you could use as a measure of their desire to play. And now you're getting into the animal's mind in a fairly profound way.

You make a connection between rat brains and human brains through a concept you call nested brain hierarchy. What is that?
By nested hierarchy I mean a way of looking at the brain, looking at its layers and how they developed over the course of evolution. Humans go back to the Pleistocene [about 2.5 million years ago], but the emotional part of the brain goes back much further, all the way to the time when ancestral mammals evolved away from reptiles. Primary processes, based in deep subcortical regions, manifest evolutionary memories that are the basic emotional operating systems of the brain. Secondary processes, based on a series of way stations known as basal ganglia, are enriched with the mechanisms for learning—for linking external perceptions with associated feelings. Then on top, the tertiary level is programmed by life experiences through the neocortex, engendering our higher cognitive processes such as thinking, ruminating, and planning. Our capacity to think is fueled by our storehouses of memory and knowledge acquired by living in complex physical and social worlds. But the ancient feeling states help forge our memories in the first place. New memories could not emerge without the underlying states that allow animals to experience the intrinsic values of life.

Researchers have recently tried to treat depression by stimulating the brain with electrodes. The psychiatrist Helen Mayberg, for instance, has found a spot that, when stimulated, seems to relieve depression.
What Helen Mayberg has been doing is at the tertiary level [the neocortex, or center of thought]. We are evaluating similar manipulations at the primary level [ancient structures]. This should be more powerful. At the tertiary level, all you can do is dampen the psychological pain coming from deep down. We are going to that deep place, where we'll try to do something more direct by amplifying eagerness to live.

You are going to address mood disorders by going straight to the source?
We plan to go smack into it. We think that depression is an underactive seeking urge that has been made underactive by too much psychological pain. We know that all the neural systems are still there, so our goal is to invigorate the primitive seeking urge to provide a positive affect to fight the negative pain. That's what we're gonna try.

FROM THE JULY-AUGUST 2012 ISSUE

Discover Interview: Tullis Onstott Went 2 Miles Down & Found Microbes That Live on Radiation

Bacteria found in gold mines and frozen caves show the extreme flexibility of life, and hint at where else we might find it in the solar system.

By Valerie Ross | Tuesday, June 26, 2012

RELATED TAGS: UNUSUAL ORGANISMS, EXTRATERRESTRIAL LIFE, OCEAN, MARS, NEW SPECIES, EVOLUTION, ARCTIC & ANTARCTIC, ECOSYSTEMS, EARTH SCIENCE

Onstott keeps a sealed workspace in his lab at high temperature and free of oxygen—just like home for the bacteria he studies.

Photo: Jess Dittmar

The first time Tullis Onstott ventured underground, he squeezed into an elevator with dozens of South African gold miners and descended a mile into a pit called Mponeng. His goal: Finding the bizarre, hardy microbes that survive in sweltering, inhospitable rock. A geologist by training, Onstott spent his early career studying the Earth's crust—until he heard a talk in 1993 about colonies of bacteria living thousands of feet below the surface. Ever since, he has made dozens of deep expeditions, sometimes paying his own way, and discovered bacteria living more than two miles beneath the surface in 140-degree-Fahrenheit heat. By investigating microbes in these harsh environments, Onstott is gleaning clues about how life could have begun in Earth's hot, chaotic early days—and about what it might look like on other worlds. Even his office is underground, in the basement of Princeton University's geology building, where Onstott met with DISCOVER reporter Valerie Ross.

The first time you went underground to look for life, in 1996, you had no idea what to expect. What was that trip like?

The miners took me into the stopes, the tunnels where they mine gold, to sample the rocks. We were looking at an organic rock layer just millimeters thick that had lots of carbon, because we figured somewhere with a lot of carbon was a good place to look for life. The stopes are a meter high and they tilt downward at a steep angle, so you go down them almost like a slide, passing from one tunnel to the next. I basically slipped into a rabbit hole and got this big chunk of rock. I put it in an autoclave bag [normally used for sterilizing equipment], stuffed it in my knapsack, and then I went down the stope further until I came out the bottom into another, deeper tunnel.

What did you do with the sample you collected?
We measured the rock's radioactivity. The Geiger counter showed it was hot as a pistol, so we sealed it up in a steel canister and filled the canister with argon gas, which pushed out all the oxygen. Organisms that live deep down are not normally exposed to oxygen, and in fact it could be toxic to them. So we sealed the rock away until we could get it back into the lab. I checked this radioactive rock inside a steel thing as baggage on a plane. This was 1996. Airport security was not like it is today.

When you analyzed the sample back at your lab, did you find any life?
We found one bacterium species similar to one previously identified from a hot spring in New Mexico. But the surprise was that this particular species could do something the other hot spring organisms could not: reduce [i.e., transfer electrons to] iron, which is present in minerals that are abundant in the mine's rocks, and uranium, part of soluble compounds found in water in the mine. That helped us understand how they got their energy.

Then you found still more perplexing discoveries in other South African mines—for instance, microbes similar to those previously seen only at the bottom of the ocean.
That's right. We went back to South Africa in 1998, this time to Driefontein Mine, located about 40 miles southwest of Johannesburg, and took water samples, which are easier to work with than rock and less likely to be contaminated. We started finding the same organisms that people were reporting from deep-sea hydrothermal vents [where hot, mineral-laden fluid flows through volcanic rock into the ocean from deep within the Earth]. We don't know how the same organisms got to be in both places, because South African crust has not seen ocean water in two-and-a-half billion years. It's very much a mystery. We published the data, and the National Science Foundation gave us more money to go back again in 2000.

What happened on your third deep excursion in South Africa?
The next time, we purchased a house in one of the villages near the gold mines and set up a semipermanent lab there. Over two years, a rotating team from my lab and six other institutions collected most of the samples that we're still working on today. One thing we did was expand on our first find and look at more radioactive samples. We began developing an idea that radiation in the rock provides energy for microorganisms. Wherever we had radiation, we tended to see hydrogen gas forming. It made me realize that radiation should produce hydrogen by breaking water bonds. Hydrogen is the key component the bacteria need to make ATP, the molecule they use for energy.

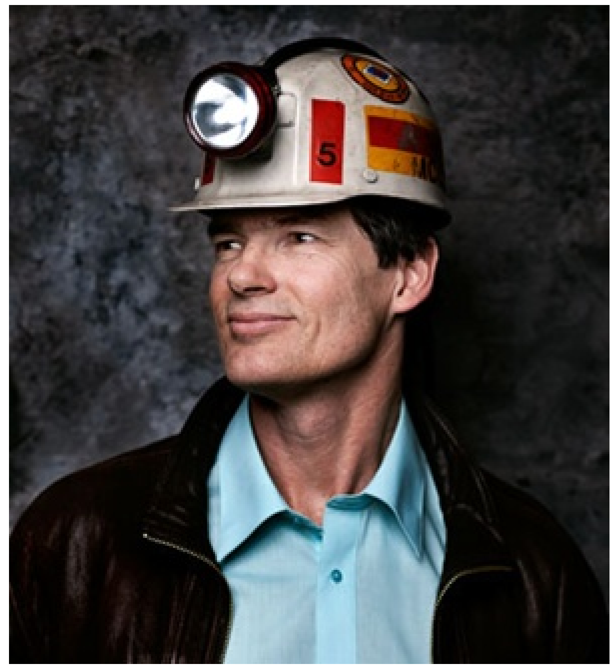
One bacterium we found is entirely self-sufficient, a one-species ecosystem. Such things aren't supposed to exist."

That's amazing, since we usually think of radioactivity as deadly—but these organisms were actually living on radiation?
Well, not just radiation, but radiation, water, and rock were all that was needed to support life at depth. You don't need light, food, or anything else from the surface. Plus, it's a renewable energy source. It turns water into hydrogen and hydrogen peroxide, which helps make the metals that the organisms consume. It is like recharging an electric battery. The radiation keeps on recharging the battery for the bacteria that then do their thing. Those bacteria could then sustain other deep organisms. That finding was really important to NASA because you can imagine any body in the solar system that has liquid water beneath the surface—like Jupiter's moon Europa, probably—will have energy for organisms as well.

Can we observe these organisms at work in the lab?
The rule of thumb is that when you get back to the lab, you can grow less than 0.1 percent of what actually exists down there. We tried all sorts of ways to grow them, gave them all sorts of nutrients we thought they might want, and we failed miserably.

Since you couldn't grow the bacteria that you found deep down, how did you learn just how they functioned?
We looked at their DNA instead, which we filtered out of the water, to determine where these things fit in with other sorts of microbial life.

Organisms so far underground, reliant on so few resources, must live a pretty limited existence, right?
Since the population of cells down there is small, most people thought they would just barely be able to eke out a living, that they were organisms with very few capabilities. But it turns out that was totally wrong. We did a full analysis of *Candidatus Desulforudis audaxviator*, an organism we found again and again in different mines in South Africa at the greatest depths—never above 2 kilometers (1.2 miles)—that made up 99.9 percent of the DNA in some of our samples. This thing had everything. It could take nitrogen directly from its environment, something we did not expect subsurface organisms to do because it takes so much energy. But the real surprise was that it had genes for flagella, tails bacteria use to propel themselves, which basically means it could be swimming around in the environment. It had genes for gas vesicles, which means it can adjust its buoyancy in the environment. And it had genes for chemoreception, which tells us it's sensing something. The genome is saying it's a very adaptable organism, and it has the capability of moving around. The idea that organisms down there might be moving around and interacting with the environment—that was really surprising. The only tip-off from the genome that this is a subsurface organism is that it has no protection against oxygen. As soon as it hits air, it's dead.



Tullis Onstott has to put on a headlamp and protective gear when excavating microbial live in some of South Africa's deepest mines.

Photo by Jess Dittmar

And does that microbe interact with other species down deep?
Candidatus Desulforudis audaxviator is entirely self-sufficient. It has its energy source, radiation. It contains everything it needs to exist, and it requires nothing from another organism. The fact that we've found it almost by itself tells us that it's a one-species ecosystem. Such things aren't supposed to exist. We thought all organisms depended on others, but this one doesn't. We've found a whole new way to live.

In addition to bacteria you also discovered more complex, multicellular organisms living 1.5 kilometers down—almost a mile underground. What are they, and how did you find them?
In 2006 I was contacted by Gaetan Borgonie, a Belgian scientist who had found microscopic roundworms, or nematodes, in caves in Central America. After he contacted me, I remembered seeing worms in biofilm, a goo-

made up of bacteria, in a mine in South Africa, too. So we went down together into the mines in South Africa to collect samples of biofilms. It turned out that the biofilms in the mines were just loaded with them. This nematode has about 1,000 cells, so it's not exactly a big guy, but still—I never would have expected to find it so deep.

The deepest organisms you have found so far are from 3.8 kilometers (2.4 miles) underground —the farthest that it's been possible to explore until now. How much deeper might life go?

At Mponeng mine, a company is now drilling a tunnel to explore for gold five-and-a-half kilometers down. Gold prices are so high that for them, it's economically feasible. For us, we think, "Yay!" The deeper, the hotter, the better. Down that far, it'll be 90 degrees centigrade, about 195°F. That's almost boiling. It's a significant increase in depth, and we're excited to see what the next several years will turn up.

What will going that deep into the planet tell us about life and evolution up here on the surface?

We're trying to see what the base of the biosphere, of all life on Earth, looks like. If DNA organisms exist down that far and at such high temperatures, we want to find them, and if they don't, we want to understand why. And if there are no DNA organisms, are there other types of organisms that might occur there in very small concentrations? There may exist a shadow biology—very, very primitive organisms that may have come into existence very early on our planet but were completely replaced by DNA organisms everywhere else.

So far you've talked only about hot environments, but what about the other extreme? Many of the places elsewhere in the solar system where we're looking for life, like Mars, are intensely cold. Have you explored any analogous low-temperature environments on Earth?

Mars has this very thick cryosphere, or permanently frozen rock layer, on its surface. So we went to a gold mine deep beneath the permafrost in the high Arctic, in the Nunavut territory in Canada. The mine has a helical tunnel that goes a kilometer and a half down. All this warm air comes up from below, and as soon as it hits the permafrost layer, where the ground is permanently frozen, all the moisture in the air crystallizes and you get huge snowflakes, a couple of feet wide. You get ice stalactites and ice stalagmites all over. It looks like Superman's sanctuary. It's easy to imagine there might be something like this on Mars as well. I had an epiphany within these ice caves: This is the kind of environment you'd want to explore if you ever went to Mars; send your rover inside the caves and have a look around. There's moisture there. There's plenty of room for life in these environments. Unfortunately, we never really had a chance to explore and look for life in those caves before that mine shut down.

Could we pick out signs of microbial life on Mars even before we go digging around in caves there?

On parts of Mars, there's methane gas that may be seasonal. It seems to appear and then go away. That means something unusual is happening: There has to be something that makes the methane and something that consumes it. The question is, are life-forms making and consuming the methane? If life is generating and consuming that methane, its chemical signature will change because of those biological processes. So as a project with NASA, we're developing an instrument that we hope will fly to Mars and measure the composition of the methane gas. If we find that it is going through a seasonal cycle and its composition is changing, that's a very good indication that there's something alive on Mars. But whatever that something is, it's going to be something quite different from anything we've seen on Earth because the surface conditions on Mars are pretty inhospitable to life as we know it.

You've looked at other extremely cold environments to learn more about life here on Earth, too. What was that like?

We've gone up to Axel Heiberg Island, a Canadian island high in the Arctic Ocean, to do some work there at the McGill Arctic Research Station, a.k.a. Mars. It's one of the largest uninhabited islands in the world, and very beautiful. It has enormous mountain glaciers, almost like a little Swiss Alps, so it's a nice change from the mines. We went up there to study microbes living in the permafrost that have been frozen for millennia.

The Arctic regions where those microbes live are warming rapidly. What impact might that have on the Earth?

There's a concern that those microorganisms will all of a sudden kick on and start chewing up organic matter, making carbon dioxide and methane. That could cause a runaway greenhouse effect in the later part of the century. Our mission is to try and understand whether that will happen. We collected 40 ice cores from the island. We're gradually thawing them to study which microorganisms are doing what, and which gases are being released and how quickly. Then we're comparing this to field measurements that we can make in the Arctic, to see if the environment seems to be doing the same things as the permafrost in the lab. A lot of groups are doing similar studies across the Arctic. We don't know the answer yet, but what we all find should further our understanding of what to expect over the next 100 years.

Has studying these various kinds of extreme, deep-dwelling microbes changed your thinking about what's necessary for life?

The more I learn, the more it seems that the requirements for life are pretty minimal. The niches that life can occupy never cease to amaze me. A place may look terrible to us, but to something else, that's their Eden.

OTHER SUBTERRANEAN HABITATS

While Onstott searches for microbes in gold mines and permafrost, other researchers are seeking out life in other deep locations. Their results are filling the picture of Earth's buried ecosystem.v. r.

1 Around Hydrothermal Vents The scalding hot, sulfur-laden waters of hydrothermal vents, where ocean water heated by magma reemerges through cracks in the seafloor, are teeming with microscopic life. These bacteria support complex ecosystems in dark, otherwise sparsely populated ocean depths. Oxford zoologist Alex Rogers and his team explored the life around a 720°F vent off the East Scotia Ridge near Antarctica (shown here). In January they reported a host of unusual animals living near the vent, including a seven-armed sea star, a "ghostly white" octopus, and a new species of yeti crab, its underside covered in hairs.

2 Under the Ocean Floor Several teams are currently hunting for life beneath the seabed. Earlier this year, geomicrobiologist Katrina Edwards of the University of Southern California and her colleagues drilled into the crust of the Atlantic Ocean and installed small subsurface observatories to monitor microbial life. In 2010 scientists from Oregon State and other institutions drilled into the gabbroic layer—the deepest layer of the oceanic crust, close to the hot, mineral-rich mantle—to find a host of bacterial species capable of gobbling up hydrocarbons from an unknown source.

3 In the Deepest Caves The world's deepest known cave, Krubera-Voronja in the Republic of Georgia, extends down a mile and a quarter. Biologist AnaSofia Reboleira of the University of Aveiro in Portugal, who has been exploring caves since she was a teenager, recently searched Krubera-Voronja for the rare, small organisms that populate it—a cold business, since temperatures in the pitch-black depths hover just above freezing. This year, she and her team reported four new species of eyeless, wingless insects at various depths, ranging from 60 meters to almost 2,000 meters (more than a mile), near the cave's bottom.

MAPPING DEEP LIFE WITH DNA

Onstott calls his trips into the gold mines "underground safaris," but finding new species in the depths of the Earth is a far cry from spotting them on the savannah. The only species Onstott has observed in action are nematode worms; he could see them squirming under a microscope, and took detailed electron microscopy images of their hundredth-of-an-inch-long bodies. He also found cells of *D. audaxviator*, a bacterium that made up 99.9% of the organisms he recovered from one of the filters used to extract water from rock fractures deep in the mines. Onstott imaged what he could of those cells with a transmission electron microscope. But he has never been able to see any bacteria moving around, or grow them in the lab. Instead, the vast majority of what he studies is DNA traces. *D. audaxviator* provided enough genetic material to yield that species' whole genome, allowing Onstott to ascertain that the organism belonged to a self-sustaining ecosystem and could sense its environment. In other cases he has found bits of free-floating genetic material from other species—just enough, he says, to show that each one exists deep in the mines and is largely specific to the fracture in which it was found. "As you move from one fracture to the next," Onstott notes, "the microbial species change."

FROM THE JUNE 2012 ISSUE

Discover Interview: Deep Underwater, George Bass Has Seen Pieces of the Past

The pioneering underwater archaeologist ignored academics who said he was wasting his time and professional divers who assumed he would not make it out of the water alive.

By Eric A. Powell | Thursday, June 28, 2012

RELATED TAGS: ARCHAEOLOGY

Photograph by Randal Ford

Much of human history is hidden beneath the waves: Some 3,000,000 shipwrecks may rest on the world's seabeds. But archaeologists had to rely on professional divers for scraps of information about these sites until the 1960s, when George Bass began to apply rigorous excavation techniques to underwater wrecks. Over the next half century, Bass led groundbreaking studies of Late Bronze Age (1600-1100 B.C.) shipwrecks off the coast of Turkey, along with sites from many other periods. Along the way, he transformed underwater archaeology from an amateur's pastime to a modern scientific discipline. Those achievements earned him a National Medal of Science in 2002. Now a professor emeritus at Texas A & M University, where he founded the Institute of Nautical Archaeology, Bass reflected on his storied career with DISCOVER senior editor (and passionate lover of archaeology) Eric A. Powell.

Why go underwater to study the ancient past, when research is so much easier on land?
Underwater artifacts are protected against the most destructive agent of all, which is us. People drop plates and break them. They drop glass bottles and break them. They burn marble columns for lime. They melt down bronze statues for church roofs. Also, there are certain things that are simply not going to be found on land, like raw materials, because they don't remain raw for very long out of the water. The other reason to go underwater is that it's the place to find evidence of ship hulls, which were as important to ancient cultures as architecture, pottery, anything. There's always been a desire to transport goods or ideas as cheaply and in as great a quantity as possible. For much of human history, that meant building the best ship you could.

What can you learn from a ship hull?
Since at least the Bronze Age, seafaring has been key to cultural progress. Ships are in some cases the most technologically advanced equipment a culture would develop—their space shuttles. So to really understand the ancients, you have to be able to understand how they approached the sea, and the only way to do that is to excavate shipwrecks. And those ships only sank once, so they can give you incredibly precise dates.

Have you always been drawn to ships and the sea?
I grew up in Annapolis, Maryland, where my father taught English at the Naval Academy. My brother and I made a diving helmet out of a tin square that we cut out and put glass in as a faceplate. We would have died if we had ever tried it. I was also inspired by a retired Australian army officer named Ben Carlin, who made an amphibious jeep that went all around the world. He put it together two doors down from us. I used to help him after I came home from school—you know, tightening nuts. He thought he'd make his fortune from it. He wrote a couple of books about that jeep, but he never did make his fortune.

Were you also interested in archaeology from the beginning?
Not at first. When I was in high school, I fell in love with astronomy. Later I went to Johns Hopkins and started as an English major. But then I spent my sophomore year of college in England at the University of Exeter, and I got what they call "rusticated" for pulling a prank. Forty of us got suspended because we raided a local agricultural college. I had nowhere to go. My brother's roommate and some of his friends were going to Taormina, Sicily, for spring break and asked me to go with them. So here I was in Taormina, sitting out there in the evening and looking at a Roman theater with Mount Etna in the background, and I thought, you can make a living studying this stuff. Back at Johns Hopkins there was no archaeology department, but they made up a major for me with courses in the Near Eastern section and the classics section.

And then you had an amazing first experience as a field archaeologist.
I went to the American School of Classical Studies in Athens and then excavated at the site of Gordion in Turkey, the capital of King Midas's empire in the eighth century B.C. I found the first piece of gold, an earring, from the level of the site that dated to Midas's time.

You had to leave archaeology temporarily in 1957 to serve in the Army. Did that slow down your archaeological career?
Truth is, that was as important as any university degree I could have had. I was plunked down in a 30-man Army security unit in the middle of a rice paddy in Korea near the DMZ, the only American unit inside a Turkish brigade. It was a hardship outpost. The night I arrived the guys all got drunk and were rolling around in the rice paddies yelling obscenities at me. I was terrified; I didn't know what to do. Well, I grew up that night, I guess. Suddenly I was in charge of generators, trucks, the food, the operation. When I got back to the States,

Rodney Young, an archaeologist at the University of Pennsylvania whom I'd worked with at Gordion, knew I'd had this formative experience. He had recently gotten a letter about a diver who'd found a Bronze Age shipwreck site off the coast of Cape Gelidonya in Turkey. Rodney asked If I'd like to go out and excavate this shipwreck.

Wait—did you even know how to dive at that point in your career?
I had to learn. So I joined the Depth Chargers at the Central YMCA in Philadelphia. My teacher was an ex-Navy diver who had lost an eardrum in a diving accident. At the end of the sixth lesson, we were still practicing snorkeling. I said to him one night, "Could I try a tank on once? I leave for Turkey tomorrow and the site is a hundred feet deep." And I found it very easy. I've never had any problems with diving.

So you started excavating at Cape Gelidonya in Turkey with only one diving lesson under your belt?
That's right—and it's in the worst current in the Mediterranean. Cape Gelidonya was the first ancient wreck excavated in its entirety on the seabed, the first excavated by a diving archaeologist. Before, archaeologists would sit on the deck like dogs waiting for a bone and accept artifacts brought up by divers for them. The divers always were saying archaeologists could never learn to dive. But we could! Cape Gelidonya showed it.

Cape Gelidonya dated to 1200 B.C., making it the earliest known shipwreck at the time. What did those artifacts teach you about seafaring culture during that era?
At the start we all assumed it was a Mycenaean, or Late Bronze Age, wreck. All the English, German, and French sources indicated that Mycenaeans, the people of the Homeric epics, had a monopoly on maritime commerce back then. The reason was that Mycenaean pottery had been found all over Egypt, the Palestinian coast, and Cyprus. So when we found copper and tin ingots, which are used to make bronze, we assumed they were being shipped to Greece to be made into bronze.

Then I started studying pan balance weights that we excavated from the site. I saw certain weights repeating themselves—multiples of 9.32 grams. That's an Egyptian qedet. Or 7.20 grams, which was another standard unit in the Near East. And a lamp from the ship appeared to be Canaanite. I concluded that it was actually a Near Eastern ship, not Mycenaean after all. At that time all classical archaeologists thought that bronze had to come from Greece, that Greece was the center of civilization. But it's really a cultural bias.

You were criticized for identifying it as a Near Eastern wreck.
That excavation at Cape Gelidonya is the thing I'm proudest of in my career, and I didn't get a single favorable review from archaeologists for my publication. But we later confirmed that the ship was from Cyprus, which was then part of the Near Eastern world. Underwater archaeologists were sneered at for so long. No one took us seriously. We were just a bunch of skin divers.

"Skin diver"—why that insult?
Skin diving was a macho thing in those days. Archaeologists thought it was a bunch of jock divers out there. They didn't understand you can work more carefully underwater than you can on land. You can excavate one grain of sand at a time. You can't do that on land. I remember when an archaeologist, who shall remain nameless, called underwater archaeology "that silly stuff you people do, bringing up amphoras." At that time we had the largest dated collection of seventh-century pottery in the world. He was publishing a book on late-Roman pottery going up to the seventh century a.d. and he was calling it silly stuff. I said, "What do you mea +

'silly'?" He said, "Well, you can't do careful work underwater." And I said, "Yeah, you can. We map things very accurately." He couldn'taccept the fact that a diver is not just some clumsy guy with lead shoes.

After Cape Gelidonya you went on to excavate other sites, including a seventh-century Byzantine shipwreck at Yassi Ada, an island off the western coast of Turkey. How did you find these sites?
Almost all the wrecks were shown to us by Turkish sponge divers. Based on the number of sponge boats, the number of divers, how long they go down, and how deep they go—all that stuff—we calculated once that if we interviewed every sponge diver about what they saw on the bottom, we'd learn as much as if one of us nautical archaeologists swam for a year. Some would say, yeah, but they are not doing scientific searches. Baloney. They were doing better searches than we ever did. Their livelihoods depended on it.

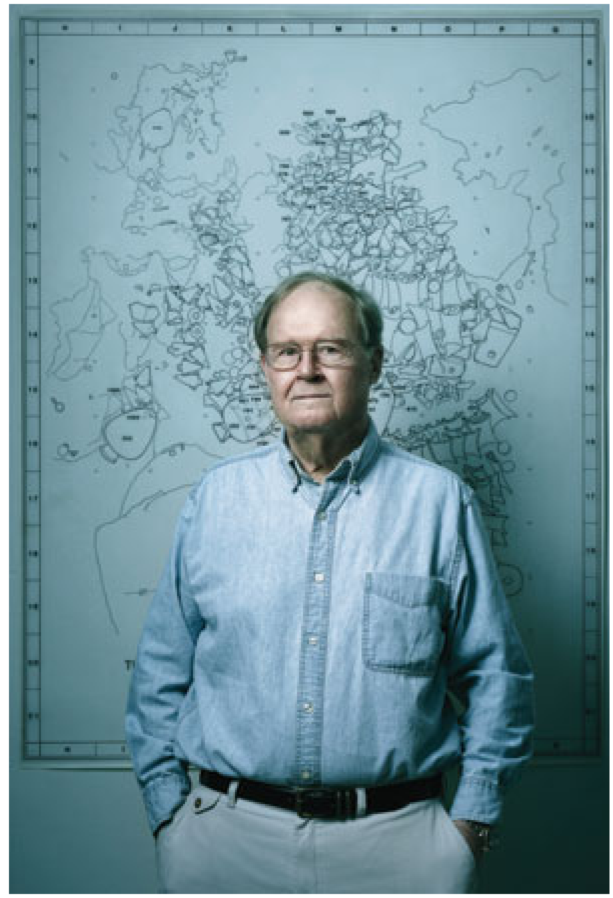
Despite your success, in 1969 you abandoned underwater archaeology. Why?
At Yassi Ada, one of our most skilled, experienced divers, Eric Ryan, was very near death when we pulled him from the water with an embolism. And then we had a sponge diver also brought to us with the bends, or decompression sickness, which is caused by nitrogen bubbles forming in your blood if you come up too quickly. It was horrible. He was calling out to his wife and Allah. He died during treatment in our decompression chamber. Eventually I thought, I've had a decade now of doing this. The odds are that one day, maybe a coed will die and I'll have to lift her dead body out of the water. Why don't I just get out of it now while I'm ahead? I've tempted fate too often.

You switched to work on land at a site in southern Italy. Why there?
It was a Neolithic [6000–2800 b.c.] site. We were trying to determine when domestic animals were introduced into that part of Italy. We thought we might be able to study the bones and pottery to find that out. It didn't work, and I remember thinking that out there somewhere in the Adriatic was probably a shipwreck that would answer this question so much better. Also, I just missed the smell of the sea and the seagulls and the rope and the smell of tar and all the things that surround boats.

So you hatched a plan to get back to your true love, underwater archaeology.
In 1972 my colleague Fred van Doorninck at U.C. Davis came and stayed at our house in Philadelphia to work on this final publication about the Byzantine wreck at Yassi Ada. And we started talking about this little dream: What if we had an institute devoted to underwater archeology? We were naive. We thought we could get a compound out on a peninsula on the Turkish coast and grow our own vegetables and buy ourselves a trawler.

How did you finally take the plunge and turn that dream into something real?
One day I got a call from a woman who said, "There's this big piece of wood that's washed up on the beach here in New Jersey." She was wondering if it might be a Viking ship, and would I come down and look at it? My friend Dick Steffy, an electrician who built accurate ship models, and I went out and quickly saw it was modern, built in Maine around 1890. Then while we were driving home in separate cars I noticed Dick waving out of the window to stop. We pulled over to the side of the highway, he walked back toward me, and he said, "George, I've decided I'm going to make a career as an ancient shipwreck reconstructor." I said, "Dick, there is no such thing. You've got a wife and children. You'll starve to death." He said, "If you don't try something, you'll just die and never know whether it would've worked." I listened to him, and shortly thereafter I decided to leave Penn to found an underwater archaeology institute.

Eventually you found a home for the institute at Texas A & M and set up a series of intensive underwater surveys and excavations around the United States, the Caribbean, and off the coast of Turkey. Which site do you view as most important?
No question, it is the Bronze Age wreck we excavated at Uluburun, Turkey, not far from Cape Gelidonya. A sponge diver reported seeing "strange metal biscuits with ears," which were copper ingots, at the site. With my colleague Cemal Pulak taking the lead, we found the shipwreck, excavated it, and discovered it had 20 tons of raw materials, things that had never been seen before: intact tin ingots, almost 200 glass ingots, and ebony logs. We had half a ton of resin called terebinth, which was probably burned as incense. These are things you just never find on land. We had 10 tons of copper and 1 ton of tin, which is exactly the right proportion for 11 tons of bronze. Like the Cape Gelidonya wreck, the ship was clearly coming from the East, maybe the Palestinian coast, and carrying goods to Greece. It was an unprecedented window onto the Bronze Age economy.



Photograph by Randal Ford

How did that change our thinking about life in the Bronze Age?
You name it—it contributed to so many fields: the study of weapons, the history of glass, the history of metallurgy, the history of ship construction, just endless.

Looking ahead, what kind of technology will nautical archaeologists need to keep the field advancing? The one I'm waiting for is a one-atmosphere flexible diving suit. That's a diving suit that would be flexible but could still withstand enormous pressure. It would allow divers to go down and excavate for hours at a time without worrying about decompression. That would revolutionize the field. Right now we can only work twice a day for 20 minutes at a time because of complications due to the pressure at great depths.

What are the greatest discoveries left to be made in nautical archaeology?
There's a whole unknown early nautical history. Crete was suddenly colonized with domestic animals in 6000 B.C., so there must have been rafts or some kind of seafaring craft at that time. Same with Australia—but it was settled 40,000 years ago or more. There's no reason why remains of the craft they used couldn't survive, if they were protected by sand and sealed from decomposition. They just haven't been found yet. It would also be interesting to know what kind of craft the Mesopotamians used. And I would love to do a survey of the Red Sea and find a pharaonic ship.

What about sites we already know about? Is there more to be discovered there?
Of course. We recently re-excavated Cape Gelidonya with better equipment, better metal detectors, and found the site is larger than we thought. We found that pottery extended to the base of a rock that rises to just below the surface. The diver and photojournalist Peter Throckmorton, who first identified the site, thought maybe the

ship had hit that rock. Then 50 years later we found a trail of artifacts from that rock to the rest of the site, confirming his hunch.

That's an incredible leap through time, to a specific moment 3,200 years ago. When you're at a site, do you imagine what it was like to be aboard the sinking ship?
Back when I was running excavations, I was more worried about keeping my crew alive. But after I retired I was looking through some family history compiled by my grandfather. I found a note: "William Jessup Armstrong, grandfather, lost in the sinking of the *Atlantic*." I'd never heard of that, so I went down to the library and learned that the *Atlantic* sailed from Connecticut just before Thanksgiving in 1846 with some 80 people aboard. Then something blew up on the ship, and it was drifting in a terrible storm not far from shore. Forty people died, and on the list, there's his name: "Lost—the Reverend Doctor Armstrong." So I visited where the *Atlantic* went down and discovered that people have collected spoons and things from the site. That led me to think about all the stuff I've collected from shipwrecks over the years.

How did that change the way that you conceptualize the past?
When I excavated a classical Greek shipwreck at a site called Tektas Burnu, my students asked me, "Do you think anyone made it ashore?" And I said, "Of course, it sank just a few feet from shore." But you know what? The shore's got jagged rocks, and with a storm, they would've had waves crashing over them. I hadn't thought about it until this. The *Atlantic* went aground on a beach, and yet still half the passengers died. It just brought it home: Every one of these shipwrecks we excavate is possibly a site of terrible human tragedy.

---

10 Undersea Tales

by Mary Beth Griggs

1. Bronze Age Merchant Ship Cape Gelidonya, Turkey Archaeologists long assumed the Greeks ran the economic show in the Mediterranean during the Late Bronze Age. Then, in the summer of 1960, George Bass excavated a ship dating to 1200 B.C. off the southern coast of Turkey. The vessel—the first completely excavated underwater—was carrying Near Eastern plaques, copper ingots, and other goods from the East to Greece, not vice versa. The site upended conventional wisdom about Bronze Age trade and marked the beginning of scientific underwater archaeology.

2. 17th-century Swedish Warship Stockholm Harbor In 1628 the ornate Swedish warship *Vasa* sank less than a mile into its maiden voyage. In 1961 archaeologists raised the ship from the seabed, making it the first major shipwreck to be recovered almost intact, and giving researchers a unique look at 17th-century naval warfare. In the early 2000s large deposits of sulfuric salts were found eating away at *Vasa*'s hull, prompting researchers to develop new conservation methods that could help save *Vasa* and other excavated ships.

3. Viking Ships Roskilde, Denmark Most shipwrecks are the victims of unforeseen catastrophe, but five Viking-era ships excavated in 1962 near the Danish town of Roskilde, outside Copenhagen, were sunk on purpose. The ships formed part of an underwater rock barrier that was constructed in the 11th century to protect Roskilde from sea raids. Centuries underwater had made matchsticks of the ships' hulls, but researchers managed to piece them together from more than 100,000 splintered bits of wood. The vessels gave archaeologists an unprecedented look at Viking shipbuilding techniques.

4. Kamikaze Fleet Takashima Island, Japan Legend has it that when Kublai Khan, the Mongol emperor of China, invaded Japan in 1281, his fleet was destroyed by a typhoon the Japanese dubbed a kamikaze, or "divine wind." Celebrated in art (such as the 19th-century engraving below), the tale persisted, unproven, until the 1980s, when archaeologists diving off the small island of Takashima found copper coins, metal helmets, and arrowheads dating to the 13th century. Last year's discovery of the substantial remains of a ship confirmed that the khan's fleet has indeed been found.

5. Union warship Outer Banks, North Carolina On December 31, 1862, the *USS Monitor* sank in rough waters off the coast of North Carolina, carrying 16 Union sailors to their deaths. The wreckage of the ironclad warship was discovered by sonar in 1973. Over the next 20 years, archaeologists removed 210 tons of relics from the seafloor, including the ship's iconic gun turret (seen in an 1862 photograph above) and more intimate objects like buttons and silverware used by the sailors on board. While conserving the ship's remains, researchers were able to study the inside of *Monitor*'s 20-ton, 400-horsepower engine, one of the most advanced of its time.

6. Sunken Caribbean Port Port Royal, Jamaica Shipwrecks are not the only important archaeological sites preserved underwater. Nestled along the southern Jamaican coast are the remains of Port Royal, a colonial city (and pirate haven) that partially sank into the sea after a devastating earthquake in 1692; some of the town's neighborhoods dropped 15 feet in an instant. Excavated from 1981 to 1990, Port Royal offers a glimpse into both the panicked moments after the earthquake and the everyday lives of Port Royal's 17th-century residents, commoners who rarely show up in historical documents. Archaeologists have made discoveries both poignant—a pocket watch from the site forever set to 11:40 a.m., around the time of day the earthquake hit—and prosaic, such as hair clippings, perhaps from a pirate's recent haircut, and intact glass liquor bottles.

7. American Zeppelin Big Sur, California Imagine the Titanic floating overhead: That's what it would have been like to see the USS Macon fly by. Nearly 800 feet long, the airship was completed in 1933 as part of an effort to equip the U.S. Navy with airborne military bases. With an onboard hangar, *Macon* was capable of launching five small fixed-wing planes in midair, but it never saw action and went down off California's Big Sur coast during a storm in 1935. Rediscovered in 1980 when a fisherman caught a piece of the airship's debris in his net, the wreck was recently surveyed and mapped using sonar and remotely operated robots. Government archaeologists continue to explore the unique site, which lies in 1,500 feet of water.

8. A Pirate's Flagship North Carolina Coast In the early 18th century, Blackbeard was the most feared of the pirates who preyed on vessels traveling to and from the American colonies. His specter returned in 1996, when archaeologists searching off the North Carolina coast discovered Blackbeard's flagship, the *Queen Anne's Revenge*, which ran aground in 1718 as the pirates fled English warships. A team has excavated at the site ever since, recovering cannons, a copper disk depicting Queen Anne herself, and personal effects such as pipes. What the crew left behind and what they took as they evacuated tell researchers what pirates of that period valued most—information that ships' logs did not record.

9. Phoenician Trader Bajo de la Campana, Spain Along Spain's southeastern coast, a treacherous rock formation called Bajo de la Campana has claimed many ships through the years. They included a 7th-century B.C. Phoenician trading vessel of a type depicted in contemporary wall reliefs. The recent excavation of the ship opened a window onto the maritime economy of the Phoenicians, a Near Eastern people who built a trading empire throughout the Mediterranean from 1500 to 600 B.C. As it sank, the ship left a trail of artifacts on th seafloor, including tin ingots, elephant tusks, and vials of perfumed oils, illustrating just how active the Phoenician trading system was. The vessel was most likely bound for a Phoenician colony just north of the wreck site.

10. HMS *Investigator* Banks Island, Canada The British navy sent *Investigator* to the Arctic in 1850 to search for a doomed expedition led by explorer John Franklin. But *Investigator* was also unlucky. Its crew abandoned the ship after it was trapped in ice 500 miles north of the Arctic Circle. In 2010 archaeologists used sonar to find the ship sitting upright in 36 feet of water. Dives at the wreck gave researchers a new look at how the British outfitted vessels for polar navigation. Modifications made to strengthen the bow and hull against ice allowed the wreck to survive virtually unscathed for 160 years.

FROM THE OCTOBER 2012 ISSUE

Geoffrey West Finds the Physical Laws Embedded in Human Cities

Like the body plans and circulatory systems of animals, our developments scale in predictable ways.

By Veronique Greenwood | Friday, September 28, 2012

Steve Jurveston/Wikimedia Commons

The son of a dressmaker and a professional gambler, Geoffrey West was born just after the outbreak of World War II and raised in relative poverty in postwar England. From those humble beginnings, he went on to a brilliant career in theoretical physics, eventually helping found the Elementary Particles and Field Theory group at Los Alamos National Laboratory in New Mexico in 1974. There he investigated some of the deepest mysteries in physics, including the underlying structure of protons and neutrons, the particles that make up the nuclei of atoms.

Then in the 1990s, at an age when many researchers begin downshifting their careers, West embarked on a brand-new quest, seeking the universal laws that govern biology. After joining the Santa Fe Institute, which focuses on the interdisciplinary study of complex systems, he went even further afield, using mathematical models to investigate the fundamental organization of cities, with surprising results. He and a group of collaborators discovered that simply knowing the population of any given urban area allowed them to accurately predict the nuanced details of its infrastructure and its socioeconomic state. Give West the raw census data from your city—regardless of its history or geography—and he can tell you everything from the number of gas stations in it to the number of patents produced by its inhabitants.

In his offices at the Santa Fe Institute in Santa Fe, New Mexico, where he served as president for four years, West recently sat down for an extended conversation with DISCOVER staff writer Veronique Greenwood. They discussed his history of tackling questions outside his field, the fundamental laws that govern cities, and his belief that population overload is draining global resources, steering us toward socioeconomic collapse.

You are an unusual academic omnivore: You have mixed physics and math with biology and population studies. How do you link those fields together in your head?
When I was 10 or 11, I used to go walking on the big chalk cliffs south of London and look across the English Channel. On the horizon I could see the ships getting smaller and smaller. Then, when I was learning trigonometry a few years later, I encountered a remarkable problem: If you know the radius of the Earth, and you're standing on the edge of the ocean, how far away is the horizon? I learned there was a formula that I could use to calculate how far away I could see. I thought: "My God. This is powerful stuff." The rest of my life I have been trying to do that in some sense. So when I look out the window now and see the city and the landscape around us, I ask, "Can we put any of this into mathematics, and can we predict anything about it?"

You moved to America and went to California for graduate school. Was that a shocking change?
When I first saw California, it was extraordinary. Because I came from old, black, dark England, still recovering from World War II. I grew up with bomb sites everywhere. And there still were bomb sites in 1961 when I left and went to Stanford. There I got involved in theoretical work on subatomic particles.

Early in your career, you cofounded the high-energy physics group at Los Alamos. What was that like?
We had some amazing people there. Many of us played an important role in helping to develop what became known as the Standard Model of physics, which is our best mathematical description of the fundamental forces and particles. And because of the huge computing power at Los Alamos, we worked on simulating the theory on a computer rather than using the traditional analytic mathematical techniques of the time.

You were involved with the Superconducting Super Collider, or SSC, a Texas-based particle smasher that would have dwarfed the Large Hadron Collider. That experience helped drive you out of particle physics. What went wrong?
The U.S. government pulled the plug on the SSC in 1993, after $3 billion had already gone in. I was feeling disillusioned, and I was getting old. I come from a working-class family where the men die young. I had always assumed that I would probably not live much beyond about 60, and I was getting into my midfifties. Somewhere, I thought, there should be a formula, based on the underlying principles of how life works, that would let you calculate the life span of a human being.

How did you start on your quest to understand lifespan?
I started to look into metabolism, the chemical processes that sustain life. And what I found were these amazing scaling laws that had been discovered in biology 60 years earlier for which there were no accepted explanations. A scaling law basically represents how various measurements in a system—say, the bodies of mammals—change proportionally as size changes. The first and most famous scaling law is something called Kleiber's law, which describes how metabolic rate, the amount of energy you need per day to stay alive, is related to an organism's size. It turns out that metabolic rate [r] is just the mass [M] of the organism raised to the three-quarters power [$r \approx M^{3/4}$]. A whale, for instance, weighs about 100 million times more than a shrew. You might expect its metabolic rate to be 100 million times greater, too. But it's only a million times bigger, because metabolic rate scales as mass to the three-quarters [$100{,}000{,}000^{3/4}$ is 1,000,000]. The pattern holds with very few exceptions across all organisms. That struck me as extraordinary.

And Kleiber's law is just the beginning. What else did you find about how biological systems scale?
On further looking around, I learned that there were all these scaling laws that people had extracted from biological data. There was one law showing that heart rate decreases as mass raised to the one-quarter power, meaning larger animals have predictably slower heartbeats than small animals. Let's take a whale and a shrew again. The whale is a hundred million times bigger than a shrew, but its heart rate is just a hundred times slower. There was another law showing that life span increases as mass raised to approximately one-quarter, which translates into larger animals having a longer life span than smaller animals. These two laws together say, essentially, that there are the same number of heartbeats in your lifetime whether you are a shrew or a whale. It gives rise to the idea that big animals live very long but very slowly, and little ones live very fast but over a very short period of time.

In 1996 you extended those ideas about the patterns of life at the Santa Fe Institute, where you collaborated with biologists for 15 years. How did that come about and what did you find?
One day I got a call from Mike Simmons, the vice president at the Santa Fe Institute. He brought me together with Jim Brown, a well-known biologist at the University of New Mexico who, in a fantastic coincidence, was looking for a physicist to work with on biological scaling. Along with Brown's student Brian Enquist, we met informally here at the institute at 9 a.m. every Friday, and talked about finding an underlying theory for the scale laws. Ultimately we built a mathematical model of the mammalian circulatory system from scratch, working from basic physical laws that described networks, flow, and so on. When we put all those rules together, we determined that the blood flow rate through any mammal's aorta scales as mass to three-quarters. That allows us to predict the blood flow rate of a mammal just by knowing its size. And the blood flow rate through the aorta defines the metabolic rate, because it's what carries the oxygen. In other words, our mathematical model gave us Kleiber's law.

So what did your mathematical model tell you about how real mammals are constructed?
That the scaling laws they follow are the natural, emergent outgrowth of networks—in this case, a circulatory network—that are constructed according to basic sets of rules.

Do these laws work in other life forms besides animals?
Yes. For instance, we extended scaling laws to plants and trees. We found that the number of branches scales to the radius of the tree trunk, which tells us that even the generic geometry of trees obeys scaling laws. When you walk through a forest, you just see this mess. Trees look like random conglomerations of branches. But in fact there's unbelievable structure there. And these equations describe it.

In 2003 you started studying cities. What led you there?
Cities are obvious metaphors for life. We call roads "arteries" and so forth. But more importantly, they are our unique creations. Santa Fe feels unique, New York City feels unique. They have their own culture, history, and geography. They have their own planners, politicians, and architects. Yet when my collaborators and I looked at tremendous amounts of data about cities, we found universal scaling laws again. Each city is not so unique after all. If you look at any infrastructural quantity—the number of gas stations, the surface area of the roads, the length of electric cables—it always scales as the population of the city raised to approximately the 0.85 power.

So even without planning it, every city's infrastructure follows the same mathematical pattern? How can that be?

The bigger the city is, the less infrastructure you need per capita. That law seems to be the same in all of the data we can get at. It is a really interesting relationship, and it's very reminiscent of scaling laws in biology. However, when we looked at socioeconomic quantities—quantities that have no analogue in biology, like wages, patents produced, crime, number of police, et cetera—we found that unlike everything we'd seen in biology, cities scale in a superlinear fashion: The exponent was bigger than 1, about 1.15. That means that when you double the size of the city, you get more than double the amount of both good and bad socioeconomic quantities —patents, aids cases, wages, crime, and so on.

And those laws apply to all cities, regardless of location?

This scaling seems to be true across the globe, no matter where you are. I think that what's responsible for it is the hierarchical nature of human relationships. First of all, you cluster in a family. On average, an individual doesn't have a powerful connection with more than four to six people, and that's just as true here in the U.S. as it is in China. Then there are clusters of families, and then larger clusters that form neighborhoods, and so on, all the way up. The structure of this network of relationships could be analogous to the behavior of the networks of blood vessels in the body. They could be the universal thing holding the city together.

Despite all the efforts of planners, architects, and politicians, cities somehow obey scaling laws."

Does your discovery have practical implications for urban planning?

You tell me the size of any city in the United States and I can tell you with 80 to 90 percent accuracy almost everything about it. The scaling laws tell you that despite all of the efforts of planners, geographers, economists, architects, and politicians, and all of the local history, geography, and culture, somehow cities end up having to obey these scaling laws. We need to be aware of those forces when we design and redesign cities.

Can your insights about the scaling laws of cities help us understand the impact of population growth and urban migration?

I believe that part of what has made life on Earth so unbelievably resilient—able to evolve and survive across billions of years—is the fact that its growth is generally sublinear, with the exponents smaller than 1. Because of that, organisms evolve over generations rather than within their own lifetimes, and such gradual change is incredibly stable. But human population growth and our use of resources are both growing superlinearly, and that is potentially unstable.

Meaning that our consumption of resources can't keep growing forever?

Right. Our theory suggests we will face something mathematicians call a "finite time singularity." Equations with superlinear behavior, rather than leveling out like the sublinear ones in biology, go to infinity in a finite time. But that's impossible, because you're going to run out of finite resources. The equations tell us that when you reach this point, the system stagnates and collapses.

If your interpretation of population growth is true, why haven't cities already collapsed?

The growth equation was derived with certain conditions that are determined by the cultural innovation that dominates each historic period: iron, computers, whatever it is. An innovation that changes everything—like a new fuel—resets the clock, so you can avoid the singularity a bit longer. But the theory says that to avoid the singularity, these innovations have to keep coming faster and faster.

+

What are the issues most likely to push us toward collapse?
I think the biggest stresses are clearly going to be on energy, food, and clean water. A lot of people are going to be denied these basics across the globe. If there is a collapse—and I hope I'm wrong—it will almost certainly come from social unrest starting in the most deprived areas, which will spread to the developed world.

How can we prevent that kind of collapse from happening?
We need to seriously rethink our socioeconomic framework. It will be a huge social and political challenge, but we have to move to an economy based on no growth or limited growth. And we need to bring together economists, scientists, and politicians to devise a strategy for doing what has to be done. I think there is a way out of this, but I'm afraid we might not have time to find it.

That sounds similar to the dire warnings of economist Thomas Malthus in the 19th century and biologist Paul Ehrlich in the 1960s. Those predictions proved spectacularly wrong. How is yours different?
I've been called a neo-Malthusian as if it's a horrible word, but I'm proud to be one. Ehrlich and Malthus were wrong because they didn't take into account innovation and technological change. But the spirit was correct, and it is unfortunate that people dismiss their arguments outright. Even though innovations reset the clock, from the work that I've done, I think all they do is delay collapse.

FROM THE DECEMBER 2012 ISSUE

Planet Hunter

Meet the man behind Kepler, the planet-finding telescope that is hot on the trail of Earth-like worlds.

By Andrew Grant | Wednesday, November 28, 2012

RELATED TAGS: TELESCOPES

In 1992 Bill Borucki presented NASA with an audacious proposal: a space telescope that would detect Earth-size planets quadrillions of miles away. NASA quickly rejected it. After all, nobody knew if there were any planets beyond our solar system. But Borucki, a veteran of the never-say-never Apollo era that put men on the moon, does not give up easily. He spent the next decade building parts and performing experiments to show that his vision could become reality. In 2001 NASA finally caved and approved the Kepler space telescope, with spectacular results. Since its launch in 2009, Kepler has spotted more than 3,000 potential planets and definitively confirmed the existence of over 100, including searing gas giants and eerie worlds with two suns. By 2016, Kepler should start delivering its biggest payoff yet: planets whose size and distance from their stars are very similar to Earth's. DISCOVER associate editor Andrew Grant caught up with Borucki at his modest office at NASA's Ames Research Center on a typically pleasant northern Californian afternoon.

What steered you toward the moon and planets? Were you always interested in space?
As a boy I was certainly interested in astronomy. My friends and I would bike to Yerkes Observatory, about 15 miles from my hometown of Delavan, Wisconsin. The skies were very dark, so you could just climb up on a roof and watch meteor showers.

Did your interest go beyond observing?
My friends and I built rockets. I remember one of our early models: about two inches high, with a little drilled hole where we put gunpowder. Gunpowder was easy to get at in those days—there weren't terrorists around. After a while our rockets got fairly big. We used steel tubes several inches in diameter, with many pounds of propellant, and radios inside so that we could pick up the signal from them. We'd call the sheriff and tell him we wanted to launch, and he would shut down the roads in the area. The real problem was if the rocket came down and killed a cow. That was a bad thing. You had to pay the farmer for that cow.

So did you ever kill a cow?
We never killed a cow.

How did you get started at NASA?
After I got a master's degree in physics at the University of Wisconsin in 1962, NASA was the only place I wanted to work. Two of their labs gave me an offer: the Aircraft Engine Research Laboratory [now Glenn Research Center] in Cleveland and Ames Research Center at Moffett Field, California. Glenn was doing propulsion research; Ames was designing heat shields for the Apollo program. They both looked like good possibilities, but my father told me to go west. I said, "Well, OK. He's got some wisdom I'll take advantage of." So I took the offer from Ames.

How did you get two NASA offers? You must have been an outstanding student.
You have to remember that at this point NASA hadn't gone to the moon. We didn't know how to build a heat shield to protect a spaceship as it went through Earth's atmosphere. We didn't understand the chemistry of the atmosphere that it would have to fly through. There was so much that we didn't know, so back then you didn't have to be a straight-A student. You didn't have to have a Ph.D. Basically, you just had to be able to solve problems, and solve them quickly and in a practical fashion.

Building an effective heat shield was in fact one of your first projects, right?
We needed to see what a spacecraft would be facing when coming back through Earth's atmosphere, so we had to recreate those conditions in the lab. The idea was to have two giant guns pointed at each other—one would shoot 300 pounds of air at Mach 15, and the other would shoot a model of the craft through that air. The friction from a spacecraft going through the air at such high speed creates a luminous shock wave in front of the heat shield. My job was to design equipment that could analyze the light from that shock wave. Those measurements could tell us the chemistry of the heated air and whether the heat shield was effectively protecting the spacecraft.

How do you set up an experiment like that, testing conditions nobody has experienced before?
We needed a gun that was almost beyond belief in terms of performance. You can't shoot that much air that fast out of an ordinary rifle. But Ames had a procurer—a person who got things—and we gave him tough tasks, one of which was to get the guns off a Navy battleship. And so he did. Then we figured out how to screw one gun into another, so one battleship gun fired into the next battleship gun, until we created a giant gun that could fire all that air through a supersonic nozzle. See, at that time we needed to beat the Russians to the moon, before they got there and planted their communist flag. So at NASA there weren't a lot of impediments. The philosophy was, let's go and do it, and do it quickly. Today, most the things you want to get have to go through the whole form system, and it costs more to process something than it does just to go out and buy it. Back then we were extremely efficient in many ways. We're not that efficient today.

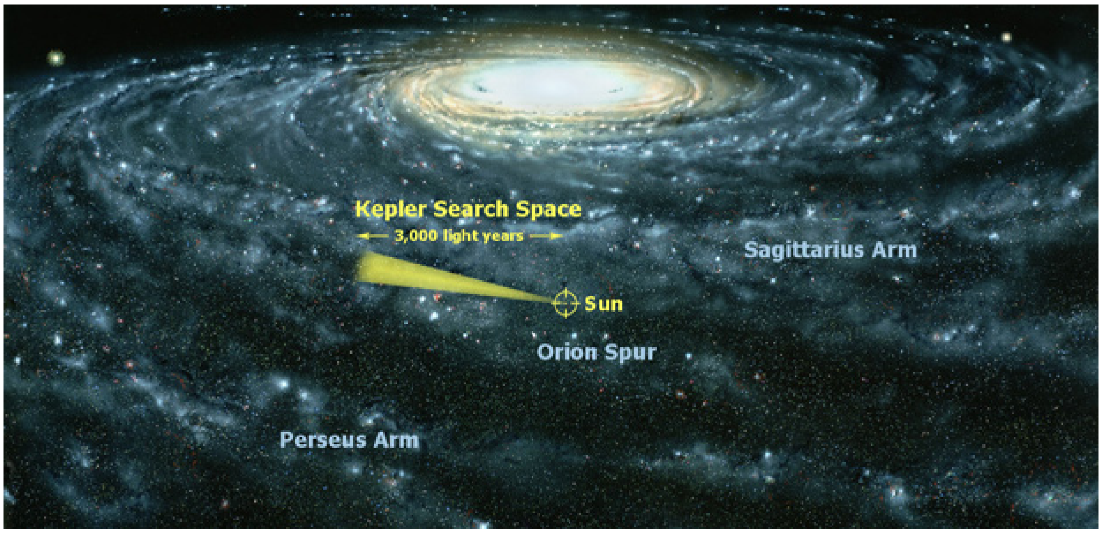
What did it feel like when you saw the triumph of the Apollo 11 astronauts on July 20, 1969?
Well, it was obviously very special to see them successfully land on the moon, walk on the moon. It was even more special to see them come back alive. That first part was great. Second part was even better.

And then the quick anticlimax, as Apollo ended in 1972. What did you do next?
NASA fired everybody who was working on Apollo. So the idea was to find some other job at Ames. It was a matter of going around and saying, "Look, I've got lots of talents. What kind of problems do you have that I could help you solve?" I ended up writing some nice papers on Earth's atmosphere and lightning on Venus, Jupiter, and Titan.

When did you start thinking about a mission to find planets around other stars?
Ames has always had seminars by prominent scientists. And in the 1970s, they had seminars about finding planets beyond our solar system. People like [physicist and futurist] Freeman Dyson were quite active in this area. Most of them were interested in trying to find planets through astrometry, measuring the change in the position of stars due to the pull of their planets' gravity. I didn't know anything about astrometry, but between my work on heat shields and lightning I did know a lot about photometry —studying the intensity of light. I began thinking that maybe photometry could be another way to find planets. I talked to some of the people in the seminars, but there was no interest. Everyone was convinced the job was going to be done with astromet

How did you develop your idea of searching for planets by looking at starlight?

Reading the literature was very helpful. I found a 1971 paper in the journal Icarus by a neurosurgeon named Frank Rosenblatt. It was a brilliant paper about how you could find planets around other stars by measuring the light from those stars. If a planet passed between the star and your telescope, you'd see a little drop in the intensity of the light. Unfortunately, just after Rosenblatt submitted the paper he went canoeing on a river and drowned. But Ames astronomer Audrey Summers and I started with Rosenblatt's paper, made some corrections to it, and then asked ourselves what kind of instrument would be required to take the measurements. In 1984 we wrote a paper concluding that you could detect Jupiter-size planets this way using ground-based telescopes. But to get to much smaller Earth-size planets, you would need a telescope above the distortions of the atmosphere, in space.



Compared with the vastness of our galaxy, the conical zone that Kepler observes is small—less than 3,000 light-years deep. Extrapolating from Kepler's early finds, our galazy hosts at least 150 billion planets.

Jon Lomberg/NASA/

What did you do then? Somehow you had to turn a general concept into a specific plan.

Ames had something called the Director's Discretionary Fund, a pot of money NASA centers could do what they wanted with. I was reasonably successful at getting small $10,000 or $15,000 grants to run a workshop or build a small photometer to measure brightness. People would come and discuss how to build a really precise photometer. It was almost beyond imagining what was required: A Jupiter-size planet transiting a sun-size star dims the light by about 1 percent, or 10,000 parts per million. But for an Earth-size planet, you need to do 1,000 times better than that—your photometer has to be sensitive down to about 10 parts per million. Little by little we started figuring out how to get down to that precision.

And then you conceived of a spacecraft that could find planets that way?

Yes, when you submit a proposal to NASA you have to lay out every component of your instrument. We knew our spacecraft would require a large telescope and light detector that would continuously monitor thousands of stars, watching for the brief planetary transits. By monitoring so many stars, you increase the chances of a transit and you have more statistical power to make estimates about the frequency of planets in the galaxy. From the beginning, this mission was designed to be a survey with the purpose of determining the frequency of Earth-size planets in the habitable zone of their stars: planets that could support liquid water, and maybe life. If the frequency is high, there's probably lots of life in the galaxy and beyond. If there are very few Earths, then it's really going to be a bear to find life.

When did you first propose a planet-hunting mission to NASA?
It was 1992, and the reviewers quickly rejected it. They said there were no detectors that could make such precise measurements. I believed there were, but I didn't have the proof yet. We proposed a revised version of the mission two years later, and this time they rejected us because of cost. NASA had just spent over a billion dollars putting the Hubble telescope in space [and had just dealt with the public relations fiasco of its out-of-focus optics]. They were afraid of the cost of another space telescope.

How did you try to change their thinking?
By 1996, when there was yet another opportunity to get missions funded, we had made light measurements using charge-coupled devices, or CCDS [similar to the light detectors in digital cameras], and showed that these detectors should be precise enough to find planets. We were also able to point to the discovery in 1995 of the first extrasolar planet orbiting a sunlike star. Another thing we had to do to help seal the deal was name the mission. For the first two proposals it was called the Frequency of Earth-Sized Inner Planets, or fresip. What a wonderful name. I thought of it myself. Everybody else hated it. Carl Sagan [who worked on the project until his death in 1996] and other members of the team said, "Bill, let's go and change that to something more exciting, like Kepler." In the 17th century, Johannes Kepler deduced the planetary laws that we depend on to interpret our data. He also established some of the laws of optics that helped people understand how to properly grind lenses for telescopes. I gave in. We changed the name and proposed the mission again in 1996.

And then you got another rejection.
Right. Having shown that the detectors worked, having shown that we could fly a mission for less than the cost of Hubble, having changed the name—it still wasn't enough. NASA said nobody had ever demonstrated that you could track thousands of stars simultaneously with good precision. They said, "Go build an observatory and prove it can be done." We borrowed a tiny, broken-down old dome with a small telescope at Lick Observatory, 30 miles from Ames. We had to seal the roof and chase snakes and rats from under the floorboards. There was no bathroom, so if we wanted to go at night we had to cross a path where there were mountain lions. But we rebuilt the observatory, built the telescope, and made the measurements. We showed that we could do photometry on 6,000 stars simultaneously. We proposed the Kepler mission again in 1998.

Was the fourth time the charm for Kepler?
No—NASA rejected us again. This time they said we needed to show that even in orbit, where it is dealing with cosmic rays and other noise, the telescope would be sensitive enough to detect Earth-size planets. At least they gave us $500,000 to demonstrate this in the lab. Ames came in and lent us another $500,000. NASA headquarters thought it would take us two or three years to design and build this thing. Then we'd miss the next chance for a proposal and go away and get out of their hair.

This time you had to build a prototype yourself, with no "procurer" to help. How did you do it?
We built a closet-size device, about 4 feet by 4 feet and 10 feet tall. At the bottom we placed a globe and shined a light in it. The light came out of the globe and through a metallic disk with laser-drilled holes. Each hole represented a star. At the top we put a little telescope and a ccd to detect the brightness of all the stars. Then we jiggled the telescope just like what would happen in space. The hardest part was simulating dips in brightness of 84 parts per million, the amount of dimming caused by an Earth-size planet around a sunlike star. If you just stick a piece of glass in front of one of the holes, it reduces the brightness by 40,000 parts per million. So we had to invent something new. We put very fine wires across some of the holes, and then ran current through the wires. When the wires got hot, they expanded by the diameter of a few atoms and blocked just the right amount

of light. With all that in place, we showed that even with vibrations in space, the detectors could make these observations.

NASA figured this would take you a few years. How long did it take for real?
We got it to work in six months, sent a technical report to headquarters, and submitted our proposal on time. In January 2000 NASA finally said, “We give up. Here’s your money.” They gave us some funding but told us we were competing against two other missions. Then in 2001 they officially approved us and set a launch date of 2006.

But then you ran into money problems.
Right after we got funded, NASA told us we weren’t going to get any money the first year. I was outraged. We had critical people who would leave. Fortunately, Anne Kinney, who was a director of science missions at NASA headquarters, acquired money—from various places we probably don’t want to go into—and gave us $1 million to get started. We ran into another problem in 2005, while we were building things rapidly. NASA informed us six months into the fiscal year that they had cut our budget in half, which means we’d already spent everything we were going to get for the year. Our only option was to fire everybody. Then the next year we had to hire new people and retrain them. That increased the total cost of the mission by many millions of dollars and caused a year of delays.

Despite all that, you had Kepler ready to go in 2009. How was the lead-up to the launch?
Kepler was set to launch on a Delta II rocket, and those rockets were having trouble at the third stage. The fuse didn’t work well. Sometimes it would light at the wrong time or not at all. Right before our launch, there were two new Deltas sitting on the pads at Cape Canaveral, one for a military gps satellite system and one for Kepler. The military told us, “You get to launch first. We want to see if the fuse works.”

That must have made you extra nervous.
There was some anxiety. But after that many years, you’re pretty used to anxiety.

What was it like watching Kepler finally make it into space after all those years of planning?
It was wonderful just to see Kepler go into orbit. But one of the biggest excitements came three or four weeks later, when we saw the full-frame image come in. All the stars were there. The spacecraft was not jiggling. It was just a marvelous image.

OK, time for the nuts and bolts. How does Kepler actually work, hunting for planets?
Kepler is like a giant camcorder constantly taking images of a group of about 170,000 stars in one patch of sky. The system takes an image every six seconds and then records the 30-minute average brightness for each star. We store all that data on the spacecraft for a month. Then the spacecraft rotates toward Earth and transmits the data to us.

That sounds like a bewildering amount of information. How do you make sense of it?
We analyze the data once every three months. There’s a lot we have to account for: Star brightness readings are affected by temperature changes on the spacecraft and the electronics, and some stars change brightness naturally. So we have to measure all those different processes and cancel them out. Only then can we look for transits, those little brightness dips that indicate planets. We have a computer program search through all the data looking for little repeating dips; repeating means that you are seeing the same planet going around and

around. If the program finds at least three potential transits around a particular star at regular intervals, then it flags that star for follow-up.

How many new planets has Kepler discovered around the 170,000 stars you're watching?
The computer has flagged about 15,000 possible planets, but a lot of those are false positives. For example, there are lots of stars that cross in front of each other, which causes a similar dip in brightness. So we get a group of scientists together at Ames to do what we call triage. They glance through all the crossing events and identify the ones that look promising. These are known as "objects of interest," and they number about 4,000. Then we have another team that looks through this data in a huge amount of detail. If the object passes that test, then we upgrade it to "planetary candidate." We have identified more than 3,000 candidates, and we believe that most of them really are planets. But we don't call any of them planets until observers can confirm them.

How do astronomers confirm a planet around another star trillions of miles away?
They use ground telescopes to look for the gravitational tug the planet would make on its star. They use space observatories like the infrared Spitzer telescope to confirm the transits. So we execute a whole stack of ground- and space-based measurements, along with some very clever analysis of the data. Only if a candidate passes all those tests do we say it's a confirmed planet. Once we say we've discovered a planet, we will bet our careers that it is a planet. It's not a false positive. If we say it's an Earth-size planet in the habitable zone, there is no way mankind knows of anything more we can do to prove it really is a planet.

What does Kepler tell us about the overall number and variety of planets out there?
Based on Kepler's growing planetary candidate list, it is clear that our galaxy contains at least 150 billion planets, and that at least half of its stars have planets. The 3,000 candidates range from well below the size of Mars to nearly double the size of Jupiter. About 1,500 are twice the size of Earth or smaller, meaning they might very well be rocky planets. Most of them are like Neptune: ice giants with lots of rock and ice but also hydrogen and helium atmospheres inhospitable to life. However, we expect that many of these Neptunes have moons. There are several groups looking for these moons, since some could be Earth-size and temperate enough for life.

What are your favorite days working on Kepler?
The highlights are the days when I see the rough drafts of papers with the proof—not the speculation, not the hope—that these planets exist. I've read things like "We found a planet orbiting a binary star." For a long time people didn't believe there could be planets orbiting a pair of stars. We proved they do. I've read papers that found small planets with a high density. For sure those are rocky planets, like Earth or Venus. Those papers get me really excited.

While you look for planets, you've also been learning a lot about stars, right?
In fact, one of the biggest surprises from Kepler is that two-thirds of the sunlike stars we are tracking are quite a bit more variable in brightness than the sun. We don't understand that. The sun is 4.5 billion years old in a 13.7 billion-year-old universe, so it's relatively young. We expected most of the stars in Kepler's field of view to be older, and older stars tend to be quieter and less variable. But we're finding that most of them are active, so maybe we are looking at younger stars than we thought.

What does that extra variability mean in terms of finding planets?
It makes it a lot more difficult to separate the small signal of an Earth-size planet from the natural noise of th +

star. It means that we'll need to see more than three transits to discover such a planet orbiting a sunlike star. We're going to need at least six transits, and I really think closer to eight, to be able to say yes indeed, we are finding Earth-size planets around stars just like our sun.

When do you expect the big announcement: Here it is, another planet just like Earth?
Earlier this year NASA gave us a four-year extension through 2016, but Kepler will need another couple of years beyond that to find the most interesting planets. This mission gets more and more valuable every single day that it runs. The data we have now are great, but not as interesting as the data we will get further out. That's where we'll be finding lots of planets in the habitable zone—the distance from the star where a planet could support liquid water and potentially life. That's the big payoff. We're finding gold dust. If we continue, we'll find gold nuggets.

You are 73 years old now. Will you still be working with Kepler when it hits its golden era?
I could have retired many years ago, and my earnings would probably be higher if I had done that. But this is an opportunity to find the answer: Are Earths common or rare? I've worked for 30 years on this, and I really want to see what that answer is. So I'm planning on being around.

Where do we go from here? Even if Kepler finds a world that is just like Earth in size and distance from its star, it can't explore it in detail. How will we find out if any of those planets are habitable or, more exciting, if they actually have life?
Kepler's job is to look deep into the galaxy and tell us what's out there. The next missions should look at nearby stars and identify the ones with planets. The European Space Agency is proposing a mission called Plato to do that; NASA has lots of options, such as the Transiting Exoplanet Survey Satellite, though they are not yet funded. After that we have to build a powerful telescope that examines the planets around nearby stars and looks for water, carbon dioxide, and oxygen in their atmospheres—signs that they could support life. That mission is going to be extremely expensive. It will challenge our technology. But it is so important that it will be done.

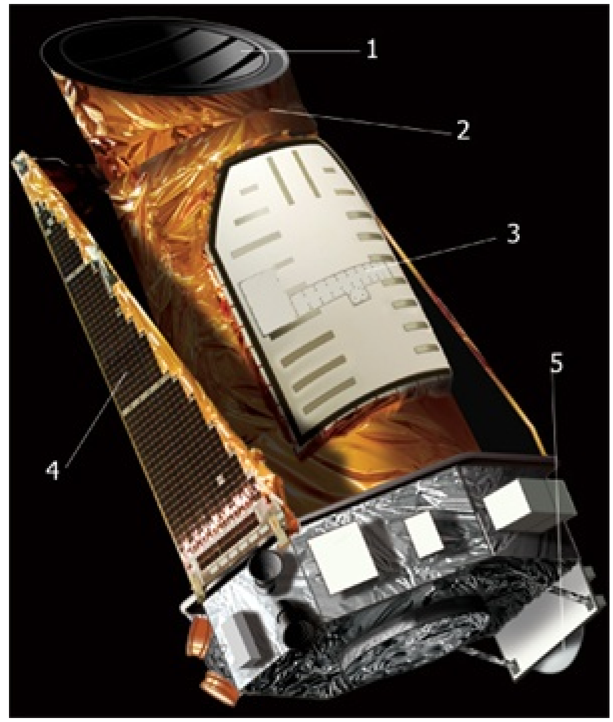
Is it frustrating to think about how long it will be before we can visit these planets for real?
Of course. It still frustrates me just that Kepler launched in 2009 when it was supposed to launch in 2006. But when you talk about state-of-the-art missions, missions that have done things no one has ever been able to do before, delays are typical.

Where do you rank Kepler among all the science missions NASA has done over the years?
It's obvious: It's number one. There is no mission that's comparable. Apollo has its own provenance, and I rank it equally with Kepler. Down, way down below, you can see the Hubble Space Telescope, which takes lovely images and tells us about the structure of the universe. That's interesting, but Kepler is the greatest mission NASA has ever flown.

Kepler 101 How to Find other Earths

1. SUNSHADE

The shade prevents sunlight from tainting Kepler's measurements. Because it is so close, the sun is about 1015 times as bright as the average star that Kepler monitors.



Courtesy NASA

2. PHOTOMETER

A light detector tracks stars in a field of view the size of 400 full moons. Every six seconds, an onboard computer reads out how much starlight was collected by each pixel.

3. COOLING SYSTEM

Kepler's sensitive detectors require temperatures of about –120 degrees Fahrenheit to operate. Ammonia and propane flow through small pipes to cool the instruments.

4. SOLAR PANELS

Solar cells provide more than 800 watts of power. Kepler's orientation remains the same as it orbits the sun, so every three months it must rotate to reposition the panels sunward.

5. ANTENNA

Once a month, Kepler stops observing for a day to beam more than 10 gigabytes of data to Earth. Complex software on the ground analyzes that data to search for signs of planets.

The kepler space telescope is an extremely complicated instrument, but the 2,300-pound observatory's core function is actually very simple: It is a light collector. The light from about 170,000 stars in the constellation Cygnus enters a 37-inch telescope and feeds into an array of 95 million pixels. Each pixel is like a bucket that collects starlight; the brighter the star, the more starlight each bucket accumulates. Most of the time, the amount of light in each pixel remains constant. Kepler scientists are interested in the brief moments when a star's brightness dips—the telltale shadow of a planet passing in front.

—Andrew Grant

Kepler's Top planets

Kepler 47: Strangest Sky Many stars in our galaxy exist in pairs, and astronomers had suspected that the competing pull of two stars would make it difficult for planets to form. Then, in August, Kepler scientists discovered a binary star circled by two planets. One of them, Kepler 47c, is probably a gas giant, but it lies in a region warm enough for liquid water. Perhaps it has a large moon that could support life. At the very least, it has some picturesque double sunsets.

Kepler 36: Most Crowded One of Kepler's more surprising results is that many stars host multiple planets crammed together in weirdly close orbits. The star Kepler 36 has two planets: an inner rocky world slightly larger than Earth, and an outer gas giant about the size of Neptune. The two planets can approach within 1.2 million miles of each other—one-twentieth the minimum distance between Earth and its closest neighbor, Venus.

Kepler 22b: Most Earth-like This world, announced last December, is twice the diameter of our planet, and its estimated surface temperature is a balmy 90 degrees Fahrenheit. Researchers at the Planetary Habitability Laboratory at the University of Puerto Rico rank it as the most Earth-like of the planets found with Kepler.

Kepler 20: Oddest Family Five planets, including two rocky worlds about the size of Earth, orbit the star Kepler 20. Unlike our solar system, the planetary types alternate: A gas giant is closest to the star, then a rocky planet, then gas, rocky, and gas. More data will determine whether our solar system's pattern is typical or rare.

Kepler 10b: Kepler's Calling Card Announced in January 2011, Kepler 10b was the mission's first discovery of a small, rocky planet, proof of the Kepler telescope's planet-hunting prowess. Kepler 10b is not a promising spot for life, though: It is so close to its star that its landscape is probably 2800-degree molten rock.

—A.G.

Do-It-Yourself Planet Hunting

It took Bill Borucki more than 30 years and $600 million to build the Kepler telescope so he could detect planets around other stars. Now that he's done the hard work, anyone can go online and start finding planets in five minutes. Or if you are feeling more ambitious, you can buy an off-the-shelf telescope, tap into the latest digital tools, and begin searching all by yourself. Here's how.

On Your Computer

Begin your adventure at Planet Hunters. In the time it takes to view the latest viral YouTube video, you can sort through Kepler data and identify planets.

Start at the site's homepage for a brief tutorial. The idea is to look at light curves, graphs that depict the brightness of stars in Kepler's view. In the rare moments that a planet crosses in front of a star—called a transit—the star's brightness takes a small dip. All you have to do is identify those dips and draw boxes around them. "Once you know what you're doing, it shouldn't take more than 10 seconds each," says Yale University astronomer Debra Fischer, who launched Planet Hunters in 2010.

The light curve below, for the star KIC 6185331, displays an obvious dip (around day 28). Six participating Planet Hunters flagged that depression, which helped scientists identify a Saturn-size world. The amateurs were coauthors on a related paper in the journal *Monthly Notices of the Royal Astronomical Society*. More discoveries, and papers with amateurs as authors, are in the works.

In Your Backyard

If relying on data from a multimillion-dollar space telescope leaves you unfulfilled, you can observe planets yourself. It costs about the same as a family vacation to Disney's Space Mountain, and you don't have to wait on those long lines.

Bruce Gary, a former NASA astronomer who has a small observatory in his Arizona backyard, has written an e-book on amateur planet hunting, available free at brucegary.net. He recommends an 11-inch telescope such as Celestron's CPC 1100 GPS (about $3,000), a superb-quality camera like the SBIG ST-7 (buy a used model online for about $2,000), and MaxIm DL Pro software ($499, cyanogen.com) to analyze your data. Observe known or suspected planets by referring to a list of transit times published at the Exoplanet Transit Database. Then submit your light curves to ETD, which pools data from amateurs and pros worldwide to nail down the properties of distant planets.

Data from amateurs is important because professionals do not have the time or money to observe every planetary transit at major observatories. In 2005 astronomer Peter McCullough of the Space Telescope Science Institute in Baltimore put out a call for help in observing a suspected planet. Four amateurs, including Bruce Gary, came to his aid. A year later they jointly published a paper announcing a broiling, Jupiter-size planet called XO-1b in the *Astrophysical Journal*. "You have to be willing to flounder," Gary says. "But once you've tasted success, you can't not do it again."

FROM THE JANUARY-FEBRUARY 2013 ISSUE

96. Voyage to the Bottom of the Sea

A high-tech sub and its famous pilot explore the little-understood world of the deep ocean floor.

By Jennifer Barone | Friday, February 01, 2013

RELATED TAGS: OCEAN, DNA

Zina Saunders

In 2011 marine microbiologist Doug Bartlett and his colleagues got a high-profile visitor at the Scripps Institution of Oceanography: director and part-time underwater explorer James Cameron, who outlined his plan to dive the Mariana Trench in his high-tech sub, Deepsea Challenger. Bartlett signed on as chief scientist, agog at the chance to collect microbes from the secluded depths.

On its first expedition this past year, the sub made 11 dives, including the record-breaking trip that made Cameron the first solo traveler to visit Challenger Deep, the bottom of the trench at 35,000 feet. DISCOVER senior associate editor Jennifer Barone spoke with Bartlett about the science behind the plunge.

A pair of explorers reached the Challenger Deep in a bathyscaphe back in 1960. Why go again?

Jacques Piccard and Don Walsh had very limited capabilities. They were there only about 16 minutes, looked around, and came back. There's so little known about the life that exists in deep ocean trenches. It's extraordinarily rare to have a human presence there. Far more people have walked on the moon.

What did you hope to learn from James Cameron's dive?

There are so many questions about the pelagic [water-dwelling] and benthic [seafloor-dwelling] life-forms: their adaptations to darkness, great pressures, and low temperatures. We wanted to collect samples of microbes in these extreme environments, culture them, and then get DNA and look at their genomic properties. We also wanted to collect animals from down there.

Deepsea Challenger was equipped with cameras to record his journey along the bottom. What was it like?

The light, silky gray sediment looked…sterile is too strong a word, but there were a few small, sparse crustaceans and a few sea cucumbers. Initially Jim followed a track we think was made by Kaiko [a remotely operated vehicle] many years ago. It was surreal that there was so little fluid flow, so little change down there, that you could still see that track.

The sub scooped up lots of microorganisms from the Mariana Trench. How are you studying them?

We have tens of thousands of microbial cells. We've been able to work with colleagues to sort out individual cells and begin to analyze their general genome characteristics. We're getting information on their diversity, which we'll use to decide which genomes to sequence in full.

What was the most exciting moment of the expedition?

To me it was Jim's very first dive of the set, a deployment in the New Britain Trench, a nearby trench 30,000 feet deep. It was in the evening in February. We all crowded around the video monitor, watching recorded video from Deepsea Challenger, and it looked like a scene from 2001, seeing this striking green sub in a vertical position.

We had also sent down an autonomous lander with the sub that had bait attached, and that bait was starting to attract animals—mostly amphipods and isopods, which are small crustaceans. It was just magical. To be out there, and to see the film from the sub and get the sediment samples it collected—it just brought home that all this hard work had really paid off. And to be involved in recovering samples and data that are so rare and incredibly valuable, it was a once-in-a-lifetime opportunity.

FROM THE MAY 2013 ISSUE

Ornithologist is Reshaping Ideas of How Beauty Evolves

After illness made him deaf to birdcalls, Richard Prum became the first to reconstruct the plumage of feathered dinosaurs and trace the evolution of feathers to beauty instead of flight.

By Veronique Greenwood | Friday, April 05, 2013

RELATED TAGS: BIRDS, DINOSAURS, EVOLUTION

Mark Ostow

Growing up in southern Vermont, Richard Prum developed an ear for birdcalls and learned from the ladies of the local garden club how to tell a warbler from a migratory hawk. Opening a field notebook at random, the Yale University evolutionary ornithologist puts his finger on the day — Nov. 17, 1974 — when he first went bird-watching at the ocean and added 20 new species to his “life list,” bringing the count to 182. That day in the seventh grade, he says, “was the greatest of my life. I’ve spent a huge amount of effort reliving that in greater depth.”

The thrill of the hunt has never faded. After graduating from Harvard in the 1980s, he set off to study South American manakins, whose courtship behaviors had never been fully described. He spent his graduate school career, and many years beyond, constructing a family tree showing how every species of manakin had evolved.

After a brilliant early career traveling the globe to record avian mating songs and dances, a devastating hearing loss forced Prum to set aside fieldwork. A less bird-obsessed man might have quailed, but Prum re-emerged with a string of discoveries that have reshaped the field’s understanding of such fundamental questions as what feathers are for and how mating rituals drive avian evolution.

If one trait has defined Prum’s scientific pursuits, it is his insistence on rejecting scientific dogma and finding answers from nature itself. Partly in recognition of his skill at bridging disciplines, Prum was awarded a MacArthur Foundation genius grant in 2009.

Recently, Prum sat down with DISCOVER correspondent Veronique Greenwood to discuss what gives some birds their astonishing colors; how modern birds descended from dinosaurs; and the evolutionary importance of beauty and female choice.

Club-winged Manakin

Nick Athanas

How did you get into birds?

I was an amorphously nerdy kid who did silly things like memorize food-eating records from the *Guinness Book of World Records*. Then in fourth grade I got a pair of glasses, and suddenly the world came into focus. Soon after, I saw the *Peterson Field Guide to Birds* in the Johnny Appleseed Bookstore in Manchester, Vt., and thought, “Wow, this is really cool.” My mom filed that away, and I got a bird guide for my birthday, and I just took off with birding. We lived in a very rural place, and there were woods and fields right outside my back door, and I became obsessed with birds. I knew a bunch of older garden club ladies who were into birds, and they had cars. So I did a lot of bird-watching with fantastic ladies who taught me plants, flowers, ferns — field biology — and I pined away for the future prospect of traveling and knowing more birds.

A career in ornithology must have felt like a natural choice.

I had no idea what real ornithology was. Through high school, I thought I was destined to be a park ranger. It wasn’t till I was an undergrad at Harvard that I was exposed to the world of science, through a freshman seminar. One of my roommates freshman week said, “Hey, here’s a course for you: Biogeography of South American Birds.” I almost fell out of my chair. I was already obsessed with South America, the most diverse place on the planet for birds — and a real challenge for the subject of speciation.

What was so surprising about the large variety of avian species in South America?

You have a huge number of birds in lowland tropical rainforests, and no obvious geographic isolation barriers that would nudge lineages to evolve differently. If you have a mountain range in the way, it’s easy to understand how speciation took place. But if you have a continuous patch of forest, it’s a conundrum.

So in South America, there is a real issue of how these many species evolved. And that was the subject of the seminar. It was given by Ray Paynter, who was a very minor figure in ornithology and, by many secondhand accounts, a really unpleasant guy.

But he had one special thing that he loved, and that was the people who took his freshman seminar. He knew exactly what it was to be a young bird-obsessive, and he welcomed me completely — gave me keys to the joint, the Museum of Comparative Zoology, which I still have in my desk drawer. I’m sure they changed the locks many decades ago, but I still have my keys, damn it.

That was a fantastic collection of birds — 300,000 or so specimens. I had turned 18 a week before, and I have been associated with a world-class collection of birds of the world continuously since then. I can’t function intellectually unless I have a couple hundred-thousand dead birds across the hall. That is my library.

The golden-winged manakin is one of about 50 manakin species, all endemic to South America. Manakins are notable for their elaborate courtship displays.

Nick Athanas (left); J. Dunning/Viro (right)

How did you picture your scientific career unfolding after taking Paynter's class?

At that point, the science I had the most view of was ecology: what birds eat, where they migrate, how they feed their young. But in my sophomore year, I learned there was a debate raging about classification.

I already knew the Linnaean classification of birds — the classical system of taxonomy that placed chickadees and titmice in one family in an order with thrushes, while ducks were in another family in a different order. The traditional view of most of the 20th century was that classification was a convenient filing system.

But this new theory, called phylogenetic systematics, proposed that the classification of organisms should reflect their actual evolutionary history. This made this rather arcane art form into a new discovery-based science, the goal of which was to discover phylogeny, or what Darwin called the "tree of life," in all its details. It got me excited about evolutionary biology because people were saying, "You can be part of this scientific revolution." That was heady stuff.

After you graduated from Harvard, you went to Suriname for six months, and then elsewhere in South America to study the courtship display behaviors of manakins — short, stubby South American birds. Watching the manakins, what stood out for you?

One of my favorite manakins is the golden-winged manakin, *Masius chrysopterus*. The male is velvety black, except his crown is yellow and red, and the inner webs of his wing and tail feathers are bright golden yellow. So when he flies, you see these flashes of bright yellow. In his courtship display, he flies through the forest and lands down on a mossy, fallen log, then rebounds, turns around in midair and lands with his bill down and his tail up.

Often he'll then fluff up his plumage like a little ball, cock his tail and bow from side to side, like a little windup toy. All of this is associated with a series of vocalizations — as he flies, he gives a single long "ceeeeeeeeee" note, and then as he jumps off a log, he goes, "ceee ceee aaak," then ends with a sort of froggy "nerk" note.

What did you learn from studying such elaborate displays of different South American birds?

When I looked at the different species of manakins and the associated male behaviors, I saw a history of what females preferred in various lineages. It's sort of an evolutionary version of Freud's classic question, "What do women want?" In some bird species, like manakins, females do all the parental care, so they can mate with whichever males they prefer.

In these species, what often evolves is a courtship display arena, or what ornithologists call a lek, where males aggregate to do their dances and females choose among the available males. Under these conditions, the males' display behaviors, songs and plumages are important in female mate choice.

Sexual selection is about who gets the opportunity to reproduce. There are a lot of males that fail every breeding season, and whatever it is about them that females don't prefer doesn't get represented in the next population. As a result, those features that females use in order to choose their mates evolve very rapidly.

If the females like long tails, tails are going to evolve to be longer. If the females like colorful plumage, the plumage is going to be more colorful. If they like this or that kind of movement, then that's what is going to happen.

As the male plumage and displays and songs diversify, the mating preferences of the females are also evolving and diversifying among species. Darwin described sexual selection by mate choice specifically: Each species evolves its own standard of beauty by which it chooses mates.

What you are suggesting, then, is that birds' sexual displays are not about solving an explicit environmental challenge to aid survival, like avoiding a predator or cracking open a seed.

Right. The beak of the finch is marvelous in that it can crack open seeds. As the seed changed and evolved in size and hardness in the environment, the beak also has to evolve in order to face that challenge. But the sexual display of a manakin functions in the mind of female birds, not in the outside world.

To understand how these aspects of biodiversity evolve, we must understand that the challenge is one of seducing a mind that has the capacity to evolve nearly infinite preferences. We see in sexually selected traits a much greater diversity than we see in those traits that are under strict natural selection.

Richard Prum is a professor of ornithology, ecology and evolutionary biology and head curator of vertebrate zoology at the Peabody Museum of Natural History at Yale University. His influential studies have spanned diverse disciplines, from developmental biology to paleontology to optical physics.

Wendy Carlson/MacArthur Foundation

Throughout graduate school at the University of Michigan and into your first professor job at the University of Kansas, you were still spending a lot of time in the field. But then something happened that changed everything.

It was in the '90s, when I was in Kansas, that I started to lose my hearing. I had a sudden hearing loss in one ear, which was likely viral. And then in the opposite ear, I developed Meniere's disease, which is a problem with controlling fluid inside the cochlea, progressively damaging the hair cells there.

By the late '90s, I was essentially ornithologically deaf. I can't hear anything over 2,000 cycles per second. If you think of a piano, if you go about a third of the way, maybe halfway from middle C to the end, by about there, I start to lose it, and at the top of the piano, I can't hear anything at all.

So you could no longer hear the birdcalls of the manakins and other avian species you'd been studying. Was that crucial to your work in the field?

It was essential. Often in the rainforests, or even in deciduous forests in the United States during migration, more than 50 percent of what you detect you'll detect by song. I wore the grooves out of bird records in elementary school, and my brain grew up to learn birdsongs, with fine ability to differentiate and then remember variations in sound. That was always my edge in field ornithology — the capacity to hear and learn birdsongs, and then find the birds.

I'll tell you a story. I got interested in a bird from Madagascar called the velvet asity. I had a suspicion that it was a lekking bird, where males gather and perform mating dances, so in 1994 I went to Madagascar to look it, and I confirmed that it was. Later I got a National Geographic grant to go do a more detailed study, and I brought over three people from the University of Kansas.

I get on the trail with them, and I go to my old reliable: this one color-banded male that I'd studied four years before. There he was, in the exact same place in the trail as before. The three assistants have never seen a velvet asity before, and they're all watching with binoculars. He kicks back his head and opens up his mouth — and I don't hear anything. At that point, I realized: This is a song that I had described in '94, and by '98, I couldn't hear it anymore. It hadn't occurred to me that it was happening so fast.

So that made fieldwork difficult to do. Now I'm a tourist. I mean I still love bird-watching, but I had to find a new connection to my life's work, intellectually.

One direction you took to fill that chasm was investigating coloration in birds. How did you become interested in that?

Back in 1992, when I had started losing my hearing, a friend lent me a jar full of newly collected velvet asities preserved in ethanol to use for some anatomical research. The velvet asity has this incredible fleshy fold of skin, or wattle, over its eye. The wattles of the birds in the jar were this deep royal blue, with opalescent highlights. And yet the label said that the wattles were fluorescent green.

I snipped off a piece of wattle and sent it to a microscopist, and we discovered a mechanism for the production of color that had never been observed before. Most organisms' colors are produced by pigments that absorb certain wavelengths of light, but not others, to create a color. Other times, colors are made by nanostructures that scatter light, a phenomenon called structural color.

I knew that's what was going on in the wattle, but what we discovered was that the structures creating the velvet asities' green wattle were made of collagen, a protein that we hadn't seen used in this way before. The collagen fibers were straight and parallel, like uncooked spaghetti in a box, arranged in a perfect hexagonal array. The distance between the fibers affects how light waves interfere with each other to cancel out some wavelengths of light and not others, thus affecting what colors you perceive.

In the velvet asity, the reason why the wattle was blue by the time it got to me was that it had been treated with formalin and ethanol, and it had dehydrated so that the tissue had shrunk in size. The spaghetti strands were closer than before, changing the color from green to blue.

And this phenomenon played out in other birds as well?

We started looking at the skins of closely related birds, and we had another surprise: Yes, they had structural colors made by collagen fibers, too, but the collagen fibers there were not arranged in a perfect crystalline order. We called them "quasi-ordered" and discovered that they also produced color by interference.

But they had this other interesting optical property, which is that they're not iridescent; they don't change color with angle of observation, like the colors in a peacock or hummingbird do. Normally, iridescence — that quality of changeable color that you see in an oil slick, or a peacock's feathers — is the clue that interference is at wo

But here, it's different.

Once we discovered that, we started looking more broadly at structurally colored feathers that were not iridescent. Many of them had this similar property. Before that, nobody had really created intellectual tools for understanding how less ordered materials could produce these structural colors.

The reason is that people were interested in order, because it's mathematically simple, and it made the problems easy to solve. But if you look at nature, new questions will arise that won't have been obvious if you're just following the intellectual path of some field as it develops.

Your next major project was also about feathers — not their coloration, but their evolution. How did you get interested in that?

The idea grew out of a lecture in my ornithology class I was teaching at Kansas, on how feathers grow. A day or two after that, I was doing a lecture on how feathers evolve. I was up at the board, jamming, when I realized that if you actually look at how a feather grows, the main 20th-century, enduring-for-80-years hypothesis about how feathers evolved couldn't be true.

The velvet asity, endemic to Madagascar, is distinguished by its fluorescent green wattle; the color is created when collagen fibers scatter light.

Dubi Shapiro

What was the contradiction?

For most of the past century, people hypothesized that feathers had evolved from elongated scales, like shingles on a house that got longer and longer until they hung off the body and provided aerodynamic function, catching air and enabling gliding and ultimately flying. But saying that feathers evolved for flight is like saying that fingers evolved to play the piano.

And what we know now about how feathers develop refutes it. A feather begins, in a chick, as a tube of epidermis that has grown out of the skin, sort of like a tubular pasta being extruded by a pasta machine. Then the tube opens up, and the outer surface of the tube becomes the top of the feather, and the inner surface of the tube becomes the underside of the feather.

So the two sides of a feather are not the same as the two sides of a scale. Like they say in the old Bert and I records, "You can't get there from here." Evolution cannot go through a series of elongated scales and ever end up with something that looks like a feather.

What were the implications for avian evolution?

That early feathers would have looked like tubes. Slightly later, feathers would have looked like fuzzy down … and so on through the steps of feather development until you get a full planar feather. The important implication of this theory is that feathers did not initially evolve for flight because you can't fly with down.

A fossilized raptor dinosaur discovered in the Liaoning province of China in 2000. Imprints of feathers encircle the body and forelimbs.

Sinclair Stammers/Science Source

As it happened, in 1998 — not long after you had started to formulate your theory of feather evolution — Chinese paleontologists discovered dinosaurs covered in fuzz, and there was quite a debate about what this stuff was. How did you get involved in that issue?

A lot of people were resistant to the hypothesis that dino fuzz could be feathers because these things don't look like elongated scales. With several colleagues at the Chinese Academy of Sciences' Institute of Vertebrate Paleontology and Paleoanthropology, we were able to establish that certain key raptor dinosaurs were fully plumaged, with feathers that were entirely modern in structure.

That was a huge discovery, which we published in 2001 in *Nature*. Along with other research, this absolutely established that feathers evolved in dinosaurs prior to the origin of flight and prior to the origin of birds.

Why did dinosaurs evolve feathers, if not for flight?

They may have just looked really cool. I think that it's quite likely that the appearance of feathers played a major role in their evolutionary origin and their diversification — that sexual selection, mate choice and other kinds of social communication were critical.

There's a great punch line here. For over a century, we *knew* exactly why feathers had evolved: Feathers had evolved for flight. But all during that time, we learned absolutely nothing about how feathers *actually* evolved. My research has approached it from a different direction. As a result of *not* asking what feathers were good for, we actually made tremendous progress in understanding how they evolved.

After Darwin proposed natural selection, he had a problem: There were all these things that were obviously not helpful to an individual's survival, like elk antlers and the peacock's tail. They were clearly a pain, or attractive to predators. He proposed that these things evolved because they provide differential success not in survival, but in the animal's opportunity to mate and reproduce.

He also proposed that different species evolved distinct standards of beauty, and that those are what led to the evolution of secondary sexual traits in diversity within organisms. Overwhelmingly, he used aesthetic language to describe what he meant — he described males as *charming* the females. He described females as having a *taste for the beautiful*. Charm, beauty — these are words that don't usually appear in science.

To the modern ear, those terms do seem like dated, pseudoscientific Victorianisms. Today the consensus seems to be that if you want to talk about aesthetics, you shouldn't be a scientist.

Right, and I think that's a terrible mistake. What Darwin was really saying is that female sexual autonomy is an evolutionary force of nature, and one of the consequences of sexual autonomy through mate choice is beauty. He also was very explicit that sexual selection was distinct from natural selection.

Very early on, his model got criticized and ultimately was ignored. The study of sexual selection was revived starting around 1975, but it's been laundered of any aesthetic content. What most biologists studying sexual selection today believe is that the peacock's tail, say, is preferred because it encodes information about quality that the female needs to know.

That's very distinct from Darwin's hypothesis, which was that it evolves because it is beautiful to that particular female. And Darwin was explicit in proposing that the traits of the male and the preferences of the female coevolve with one another; that they mutually change with one another over time.

Are you saying that there's no utility to these traits beyond their beauty — that they play no role in the animal's survival?

I think there is a huge amount of support for the notion that most of the ornament in these secondary sexual traits is actually just arbitrarily beautiful. The way in which arbitrary sexual selection has been eliminated or rejected by the field is explicitly anti-Darwinian. I'm working on the idea that we need to revive Darwin's explicitly aesthetic view of sexual selection.

The four-winged, chicken-size dinosaur *Anchiornis huxleyi* lived during the Jurassic period in China. Richard Prum and colleagues deduced the dinosaur's feather colors by analyzing fossilized microscopic structures called melanosomes, which impart color.

Julius T. Csotonyi/Science Source

These concepts, which explain how speciation could take place without physical barriers in the outside world, make you a maverick in the field.

A few years back I was describing my ideas to a well-informed behavioral ecologist in this field, and when he got my core idea, he said, "But that's nihilism." I realized, "Wow, this idea is incredibly threatening to many people's core rationale for why they study evolutionary biology." A huge number of those in the field think the mission is establishing the importance and breadth of natural selection in nature — not describing the processes that make nature the way it is.

Web Extra: Richard Prum describes how he and his team discern color from feathers' fossil remains in this video.

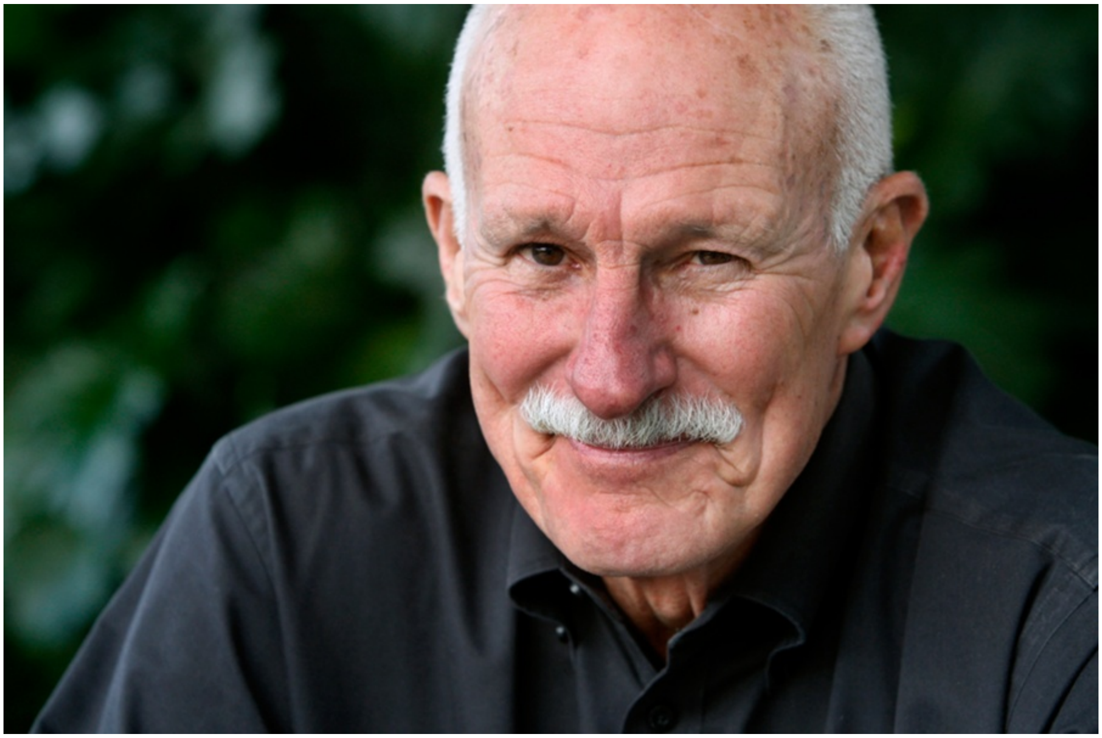
FROM THE JUNE 2013 ISSUE

Master of Disaster

Earthquakes and hurricanes will always wreak havoc, but risk management expert Robert Bea says the greatest tragedies result from hubris and greed.

By Linda Marsa | Thursday, May 23, 2013

RELATED TAGS: NATURAL DISASTERS



Paul Chinn/San Francisco Chronicle/Corbis

Robert Bea has an unusual specialty: He studies disasters. As one of the world's leading experts in catastrophic risk management, the former Shell Oil Co. executive sifts through the wreckage to unravel the chain of events that triggers accidents. The blunt-spoken civil engineer has spent more than a half-century investigating high-profile engineering failures, from the space shuttle *Columbia*'s horrific end to the explosion of the Deepwater Horizon oil-drilling rig in the Gulf.

A professor emeritus of civil engineering at the University of California, Berkeley, Bea's disaster autopsy methods — such as looking at the organizational breakdowns that lead to calamities — have been widely adopted. Although policymakers and corporate honchos seek his counsel, sometimes they don't like what he has to say — witness the flak he took from BP during the Deepwater Horizon probe.

Now in his mid-70s, Bea's voice is raspier, but his critical faculties are undimmed. On a crisp fall day, he talked with DISCOVER in his comfortable one-story house in Moraga, a leafy suburb east of Berkeley, about what causes catastrophes.

You have said that engineering failures aren't the chief culprits behind disasters, pointing instead to human and organizational failures — inadequate safety protocols, corporate hierarchies, conflicting egos or just plain laziness. Was there an "aha moment" when this became apparent?

When I was involved in the investigation into the Piper Alpha disaster, when an explosion destroyed an Occidental Petroleum oil-drilling platform in the North Sea, killing 167 men in 1988. The external investigation team that had been hired by Occidental into what caused Piper Alpha found it was a corporate culture that had gone bad, had lost its way.

I was part of that team all the way through the Lord Cullen Commission hearings in London, and I had to listen to one of my friends explain to the Cullen Commission why he and his colleagues had turned off the smoke alarms on the platform because the operating crew was doing a routine maintenance procedure late in the evening. Unfortunately, for over a month, certain alarms had been disabled to prevent unnecessary shutdowns on the rig — in some cases as a response to practical jokes. But turning off the alarms was one of the reasons they got caught by surprise.

Ironically, two years before, I was brought in to advise Occidental on risk management for Piper Alpha because they were having gas releases, pipes were leaking. Of course, you didn't have to be very smart to say, "Yeah, we've got a problem — it's called rusty pipes. And we've got problems with people not doing what they should be doing, and people who don't understand what's happening."

One evening, during the first year of the investigation, I saw spread out on the reception table of the Occidental offices a copy of the *London Times* newspaper with a great, big, bold headline that said, "Occidental puts profit before safety."

It had a picture of one of the bandaged, beat-up, horribly scarred survivors from the disaster who was telling this to the newspaper. What this survivor was observing is true. If you don't have profitability, you don't have the resources to invest in achieving adequate protection. What the tension is, is having the discipline and the foresight to make those investments before you're in trouble.

When I came back to Berkeley after the investigation was completed, I realized that for the past 50-some-odd years of my career, I'd been working on 10 percent of the problems. I'd been working on normal engineering things, and 90 percent of the problems are humans and/or organizations.

We often have ample warnings before catastrophes hit, but we tend to ignore them until it's too late. Why?

The problem is attention span, particularly in this country because we are a pretty young country. Our knowledge of history is very limited. We are extremely blessed. Lots of good things attract our attention. It's a noisy environment, really noisy. It's unusual to find people who are comfortable sitting in a room by themselves thinking.

+

You could say the eruption of Mount St. Helens was certainly painful, but it actually affected relatively few people and then disappeared into that strong noise environment. At that point people say, “Well, it’s never happened to me.

I can’t even remember my parents talking about it, and I’ve got these new things to play with, and they require attention,” like Facebook and Twitter. And suddenly, we have flitted from something that is difficult and painful to think about back to something that is enjoyable.

You seem to be suggesting that people have trouble dealing with issues over the long term. Are there other examples?

Well, global climate change is a perfect one, or rising sea levels. It’s happening slowly. People love living by the beach, so they build a beautiful home on a concrete slab, on top of the sand a few feet above sea level, and [ignore the fact] that the sea level is [rising]. So thinking about these slowly evolving long-term things, it is painful. It says, “Well, I might have to move my home. I really enjoy the beach,” and we don’t like to give those things up.

Robert Bea helped investigate the 1988 Piper Alpha disaster, where an exploding oil platform killed 167 in the North Sea.

Press Association/AP

Is this inability to think long term also true of organizations — corporations or government agencies?

Yes. The equation for disaster is A + B = C. A is natural hazards, things like hurricanes, gases and liquids under pressure that are extremely volatile. They’re volcanoes. They’re tsunamis. They’re natural, and there’s nothing unusual about them. B is organizational hazards: people and their hubris, their arrogance, their greed. The real killer is our indolence.

So human error is the kindling that escalates a natural hazard — a hurricane, a tsunami, chemicals under pressure — into C, a catastrophic disaster. Can you give me some examples?

Hurricane Ike. Galveston, Texas, got completely wiped out in 1900. Thousands of people got killed. So the U.S. Army Corps of Engineers built a seawall on Galveston Island, and that sucker has gone through every major hurricane since 1900.

But people think that if a storm hasn't happened since they lived there, somehow it can't happen to them. This is where B comes in — the hubris and shortsightedness. Because a hurricane hadn't flattened the city in decades, civic leaders decided to let people build at sea level again. And when Hurricane Ike came through in 2008, it was just like Berlin at the end of the second world war. Everything was gone.

Before Superstorm Sandy, I wrote that the subways were going to flood, but no one did anything. Mayor Bloomberg even hired some of my engineer friends from the Netherlands to come to New York City and advise him about building gates to cut off incoming hurricane surges.

But here we're back to B — hubris and shortsightedness. People think because they've never seen a storm like what happened in New Jersey or they've never seen the tunnels flooded in New York City that it can't happen, or that they need to think about building a levee.

When I lived in New Orleans, we lost everything in Hurricane Betsy [in 1965]: our house, wedding photographs, marriage license, birth certificates. Yet 40 years later, after Katrina, I go back to the same place. There's a new home built on the foundation, and the owners are dragging wet, oily mattresses out the front door.

Luckily I had no one with me that morning, but I broke down and cried. It wasn't tears of sadness. It was tears of frustration at such a miserable, despicable mess. While we can't prevent disaster, we can do things that are more sensible to mitigate risks, like maybe not building homes in floodplains.

But the cities are already there. Are you going to move entire cities?

In some cases, yes. We did it in the Mississippi River Valley after the 1993 floods. We actually moved entire towns to higher ground, like Valmeyer, Ill., and Rhineland, Mo., because we suddenly recognized they'd rebuilt them five times in the same damn place. Doing it six times doesn't quite make sense. But there is not a "one size fits all" answer.

In other cases, there are intermediate solutions that can work, such as occupying only what you can defend properly and in a sustainable manner. An example is the "new New Orleans," where parts of the city outside of the defended perimeter of the levee system can be expected to flood severely and frequently. Individuals there are building structures on higher ground and making them stronger, and preparing to take care of themselves in future storms.

But even after Superstorm Sandy's devastation, you can't just completely rebuild Lower Manhattan.

No, you can't. But you can follow the example of the massive Thames Barrier that has been built in London [10 steel gates that prevent the city from being flooded by tidal surges].

But that cost over 500 million pounds — about $850 million — when it was completed in 1982. Doing the same in Manhattan would cost up to $17 billion and an additional $10 billion to $12

billion to shore up areas next to the barriers, an astonishing amount of money.

Well, do you want to fix it now or fix it later, when it will cost 100 times as much? Damages from Superstorm Sandy in New York and New Jersey are estimated at $60 billion to $70 billion. The key question I always ask is, "Can we work this problem out in a responsible way, or do we wait until it fails — in other words, will we fix it now versus pick up the pieces later?"

We looked into this "pay me now or pay me later," and in many cases, it's more than 100 times the cost to fix afterward. We economically documented several major accidents where the factor is bigger than 1,000, like Katrina.

Disaster specialist Robert Bea studied the devastating aftermath of Hurricane Katrina, which left New Orleans flooded in 2005.

NOAA

People regularly ignore risks, but isn't it the extreme scenario — the thing that has the 1 percent chance of happening, the so-called long tail at each end of the bell curve — that causes all the trouble? What about events beyond the realm of normal expectations, like Superstorm Sandy?

Sandy is better classified as a "predictable surprise." There were some groups in the greater New York area that had a clear understanding of the potential for significant flooding due to an intense storm. But there were other groups who had no idea and made no significant efforts to learn how vulnerable the city was to storm surges from the Atlantic.

A hurricane flattened Galveston, Texas, in 1900. Hurricane Ike in 2008 took out the city again.

What do you do when it becomes more costly to prepare for every disaster than just to take the risk? How safe is safe enough?

In many cases, you can't prepare because no one's willing to spend money to do this. We've rebuilt the levees around New Orleans, for example, but they're right back on the same slabs. And it's going to cost about 10 percent of the construction costs per year to maintain them.

Now where are you going to get $1.5 billion a year? So they can't maintain it, and the next time it is challenged — and there is no doubt in my mind it will be challenged severely — it's going to fail again, and the consequences are going to be worse because we've allowed more population and more infrastructure.

Library of Congress

In aviation, which has unequaled safety records, they do predict and plan for the worst case because they can't afford accidents. But Sully Sullenberger's "Miracle on the Hudson," when the pilot landed the plane on the Hudson River after flying into a flock of geese, does seem like a miracle.

It was a miracle, but it was not an accident. It was, in fact, rehearsed. That's how the FAA was able to clear air traffic control, how he and his co-pilot, together with the flight crew, were able to get almost everything right, how the French Airbus had those backflow valves already designed in the fuselage.

We don't normally land airplanes in water. They're supposed to be on land, but they designed it to land in water as well, and the crew had rehearsed and planned what they would do in the event of a water landing. They are thinking about the impossible.

What warnings are going unheeded now? The antiquated levee system protecting California's Sacramento Delta, which is the source of fresh water for 28 million of the state's residents, comes to mind. I know you've been studying this.

An earthquake, a megaflood. Any of these natural disasters could rupture the delta levees and take a lot of the infrastructure — power lines, communication networks, gas pipelines, hydroelectric power systems — with it. Millions could be without power or fresh water for months. It isn't going to be pretty, and it will knock out of commission the ninth-largest economy in the world.

And it could happen at any time.

Yeah. Tick, tick, tick.

US Coast Guard

Bea goes back in time to explain how we might have avoided notable catastrophes of the past.

Deepwater Horizon, 2010

The Deepwater Horizon oil-drilling rig exploded in the Gulf of Mexico, killing 11 crewmen and igniting a fire that could not be extinguished. Two days later the rig sank, leaving the well gushing in the seabed. It ultimately leaked 210 million gallons of oil in the largest offshore spill in U.S. history.

» What was ignored? BP, the industry and federal regulators understood the potential for an uncontrolled blowout in Deepwater drilling, but they failed to heed warnings about the structural weaknesses in the cement casings that protect the well pipes. Plus, the blowout preventer hadn't been working properly for several days.

» What would have improved the outcome? Delivering the required degree of safety consistently and ensuring that protocols were followed. Understanding that wells pumping 162,000 barrels of oil a day are under much higher pressure, and therefore are much more dangerous, than wells delivering 500 barrels a day. Building stronger protective structures to withstand these intense pressures could have prevented the disaster.

Midwest Floods, 2008

+

Months of rainstorms led to heavy flooding in seven Midwestern states, including Illinois, Minnesota, Indiana and Missouri, resulting in 24 deaths and more than $6 billion in damage.

» What was ignored? The lessons from floods in 1993. The increasing fragility of the aging levee system, and more people building in low-lying areas susceptible to flooding.

» What would have improved the outcome? Giving the water the room it needed to flood and not build in those areas. Building and maintaining high-quality flood protection systems in the areas that could have been protected.

Columbia Disaster, 2003

The space shuttle disintegrated upon re-entry into the Earth's atmosphere due to missing heat shield tiles, killing all seven astronauts on board.

» What was ignored? The mantra "better, faster, cheaper" drove the management decision to "bring the bird back," even though the U.S. Air Force had photographs showing the leading edge of the *Columbia* was missing heat shield tiles, which were damaged during the launch. Problems with heat shield tiles during earlier missions hadn't been adequately addressed, and NASA ignored engineers' requests to ground the mission until these problems were solved.

» What would have improved the outcome? Fixing heat shield tile problems uncovered during earlier missions. Develop a backup plan for fixing the shuttle in space if it is damaged and ensuring the crew's safety. They were lucky with previous missions that had missing tiles, but they took a chance, and their luck ran out.

Exxon Valdez Crash, 1989

The *Exxon Valdez* oil tanker ran aground in Prince William Sound, spilling an estimated 11 million gallons of crude oil along Alaskan shores. Numerous factors complicated cleanup, including the size of the spill, the remote location and a lack of readily available equipment and effective chemical dispersants to dissolve the thick oil.

» What was ignored? The dangers of Bligh Reef, where the ship hit the rocks. Taking shortcuts to save time to get the oil to Southern California refineries. Not traveling in regulated shipping lanes.

» What would have improved the outcome? Better communication between vessel captains and traffic control centers to avoid treacherous conditions. True pollution control to improve visibility, and better preparation for cleanup.

+

FROM THE JULY/AUGUST 2013 ISSUE

Graphene and Nanotubes Will Replace Silicon in Tomorrow's Nano-Machines

Physicist and novelist Paul McEuen says one day nanobots will carry medicine through your bloodstream and rebuild your brain's circuitry.

By Doug Stewart | Wednesday, December 11, 2013

RELATED TAGS: NANOTECHNOLOGY, ENGINEERING, COMPUTERS

Paul McEuen, professor of physics at Cornell University and director of the Kavli Institute at Cornell for Nanoscale Science.

Michael Okoniewski

In the 2011 thriller novel *Spiral*, a scientist is forced to swallow a swarm of razor-clawed, fungus-tending micro-robots, a scene that hardly presents small machines in a positive light. So it may seem odd that the book's first-time author, 49-year-old physicist Paul McEuen, is a leader in the field of nanoscience, the study of structures smaller than a micron, or a millionth of a meter.

One might think his fellow scientists would be disturbed that he mined his field for gory ways to kill people. "Actually," McEuen says, "they were very supportive. I even got a good review in the *Journal of Mycology*." Relaxed, thoughtful and highly literate — in a recent academic article he cited Hume, Joyce and Beckett along with Nobel Prize-winning physicists Richard Feynman and Niels Bohr — McEuen is a man of wide-ranging interests who has narrowed his scientific focus to the very, very small.

McEuen was already a leading authority on carbon nanotubes, naturally occurring cylindrical structures smaller than a billionth of a meter in diameter, when he was lured to Ithaca, N.Y., in 2001 to direct Cornell University's Laboratory of Atomic and Solid State Physics. In 2010, he also took over as director of the prestigious Kavli Institute at Cornell for Nanoscale Science.

Today, he spends many of his workdays exploring the properties of graphene, the world's thinnest material at just one atom thick. Sixteen faculty and their research groups are involved in the institute he runs, creating tools that will one day build and control nanobots and other atomic-scale machines still the stuff of science fiction. One ambitious multibillion-dollar effort that McEuen is helping to plan will use nanomaterials to listen in on millions of brain cells at once.

When he's not investigating atomic-scale objects in his lab, McEuen tinkers with his next thriller manuscript in the home he shares with his psychologist wife, Susan Wiser, and their six dogs. DISCOVER sent writer Doug

Stewart to Ithaca to ask McEuen about where nanoscience is headed. The nonfiction future, to hear McEuen tell it, is a world of bloodstream submarines; tiny, flexible computers; and thinking small.

Have you always been drawn to tiny things?

I remember being fascinated by ants and wasps and other bugs when I was a kid. I'd set out a Coke can and stand back 20 feet and use my telescope to watch wasps land on it. Here were these amazing little bitty machines that could do all sorts of things. I think it's very telling: I got this telescope to look at the stars, but I ended up using it to look at small things. Even at the time that's where my interests lay — that extra universe that exists at the small scale rather than the big scale.

But you didn't end up deciding to become an entomologist.

No. As an undergrad, I studied engineering physics at the University of Oklahoma, and all my degrees are from engineering departments. My father wanted me to join him in the oil-field business in Oklahoma, but I wanted to be a scientist. Later, when I was thinking about graduate school, I read about a professor at Yale named Robert Wheeler, who was making tiny one-dimensional conductors and transistors — really skinny wires, basically. I didn't know what that was, but I thought it sounded really cool. He became my Ph.D. adviser in the late 1980s.

What excited you about the skinny wires?

There was a sense that an unexplored world was just opening up. If devices are small enough, the effects of a single electron start to matter. At MIT, where I did postdoctoral work, we made transistors that were so small there were only one or two or maybe three electrons in them. Transistors are used to turn on and off the flow of electrons through a device, and also to amplify that flow so that you can send one signal to many devices. They're the building blocks of computers. The smaller you can make a transistor, the faster it is.

This was your first foray into atomic-scale technology. What does nanotechnology encompass, and why does it matter?

Nanotechnology is the idea that we can create devices and machines all the way down to the nanometer scale, which is a billionth of a meter, about half the width of a human DNA molecule. In the case of electronics, nanoscience has already pushed it down to the nanoscale — we've been able to pack incredibly dense arrays of devices on chips. The goal is to make machines at that scale that will do real work.

After you joined the faculty of the University of California at Berkeley in 1992, your attention turned to carbon nanotubes, carbon cylinders 10,000 times narrower than a human hair. What happened?

Carbon nanotubes occur naturally — we now know you find them in soot. When I was at Berkeley, Richard Smalley, a Rice University chemist, was learning how to grow large quantities of carbon nanotubes in his lab. We thought, "Let's try wiring up some of those."

What was it about these nanostructures that excited you?

Carbon nanotubes are amazing because they're really good electrical conductors, yet they are only a few atoms in diameter. You can make transistors out of them in the same way you can with silicon. At Berkeley, we made the narrowest device anybody had ever made. It was basically a single molecule. It is fundamental science like this that underpins the applications that are coming.

Can you describe those applications? How might carbon nanotubes be used?

One approach is to use them to make high-performance, small devices that would replace silicon. You could use them the same way as you would a silicon transistor but with higher performance — like silicon transistor chips. IBM is working on things related to that. And because they're so flexible, you can use them for high-performance, flexible electronics, so if you want your electronics to be on a flexible screen, it might be useful for that. They might also be useful for nanoscale sensors: They're so small that even if a single molecule sticks to them, it can change the conducting properties, allowing you to sense the presence of individual molecules.

Since 2001, you've been at Cornell. What are you investigating?

Lately we've been working on graphene, which is a sheet one atom thick, made entirely of carbon atoms arranged in a hexagonal structure like chicken wire. You can think of it as a carbon nanotube that's been rolled out flat. Unlike nanotubes, you can make it cover large areas, you can make it more uniform, and it's much easier to work with as a material — it's as different [from nanotubes] as a sheet of paper is from a stick.

Graphene is a phenomenal material in almost every way. It's electrically conducting, so it could be useful in electronic devices. It's incredibly flexible, so something that handles like a piece of paper could actually be an electronic display. When you push a single sheet of graphene with a probe, it crinkles up a little like cellophane, but it doesn't rip. In fact, both graphene and carbon nanotubes are extremely strong. You can do all sorts of nasty things to them — pour acid on them, keep them underwater — and they don't mind.

In his 2011 novel *Spiral*, Paul McEuen envisioned swarms of miniature servants in the form of micro-robots like this one.

Dial Press

How is graphene's durability useful?

It means it can survive all kinds of environments and not break down, which is hard to do at the nanoscale. Most of the nanomachines in your body — by that, I mean biological machines like enzymes — don't last more than a few hours. They're constantly replaced in your body as they break down chemically. If you want a device to work inside your body for years, like a brain implant, durability is essential.

What kinds of nanomachines could arise out of basic research on graphene?

Since nanomachines don't exist yet, we can't say what they'll look like. You might think that they would look like miniature versions of machines we know, so if you were building a tiny machine that was going to move around in the bloodstream and look for cancerous cells, it might look like a little submarine. But it's more likely that it would look like its biological equivalent: a bacterium, with soft movable parts that flex to cause it to swim, and a little propeller.

What are you working on?

The structures we work with are the elements out of which you would build these machines — the panels and screws, you might say. Lately, we've been making lots of tiny graphene resonators. They're basically drumheads an atom thick. It's fascinating to make what amounts to the world's thinnest drum, to see if you can put it into vibration and play it and listen to it.

You can tune nanodrums just like a real drum, depending on how much tension you put in the membrane. They vibrate at the frequency of an FM radio signal, so they could be used for miniaturized communications systems. For example, if you wanted to make a bloodstream submarine, you'd need to get information in and out. A graphene resonator on board could tune to signals at a particular frequency, the way a cell phone does, but it would be extraordinarily tiny and use very little power.

You've also been designing hinges made of graphene, which would be a necessary part of any kind of nanoscale machine. How do graphene hinges work?

A traditional door hinge is a complicated device with a lot of parts, so it's hard to build — you have to build all those pieces and know how to put them together, and that's not easy to do. A graphene hinge is more like a paper fold. We made one hinge that we tested by opening and closing it about 10,000 times to show that it's indestructible with normal use.

With hinges like that made out of silicon, you might build an array of tiny steerable mirrors that would change the colors and reflectivity of pixels in a new kind of TV screen. Or, if you built a nanosubmarine, you might want to seal a drug inside for delivery to a cancer cell that you wanted to kill. A hinged graphene door could then open and release the drug on the spot. You could plan multiple folds, like an origami design.

You've been involved in designing ways to use nanoscience tools to understand the brain better. What is the main goal?

The medical world would like flexible brain implants so they can shove them between the brain's ridges or corrugations and get back signals from deep inside the brain. A flexible electronic implant might help a person control a prosthetic limb, for example. We've done no actual work on this yet — we're thinking ahead.

What's a key challenge in designing such brain implants?

One is that you want the wires to be small enough that they don't cause brain damage when you jam them in. But if they're too small, it's hard to insert them — it's like pushing a rope. What you really need is a little semi-autonomous device that knows how to crawl down into the crevices in your brain, dragging its little electrical or optical wire behind it, attach it to the right place, come back out, grab another wire, and so on. This is science fiction right now, but it could happen.

No wonder you've begun writing in the science fiction genre. Your novel Spiral features homicidal "MicroCrawlers." Did you worry about damaging nanotechnology's image?

I probably worried more about damaging my own reputation as a scientist. But I figured what the heck — *Jurassic Park* probably drew more people to science than scared them away. Anyway, people expect thrillers to be over the top.

Did you see your MicroCrawlers as benign machines gone astray, or did you intend them to be creepy?

I definitely went for creepy. They are basically robotic spiders. In fact, my wife has a fear that if she sleeps with her mouth open, a spider might drop in. That might be where I got the idea of these tiny robots getting inside people.

Did you yourself ever accidentally inhale a nanodevice?

They're so small I wouldn't notice. In any case, if I lose something or it doesn't work, there's always another one. That's an advantage of working with tiny things: You make them by the millions.

[This article originally appeared in print as "Thinking Small."]

FROM THE OCTOBER 2013 ISSUE

Harper Reed: Q&A with Obama's Game-Changing Tech Guru

How the hipster mastermind behind high-tech data-mining may have forever changed how elections are run.

By Linda Marsa | Tuesday, September 10, 2013

RELATED TAGS: PRIVACY, TECHNOLOGY

Reid Compton

With his rooster-like crest of red hair, trendy piercings and penchant for T-shirts and hoodies, Harper Reed hardly looks like the kind of guy who could topple empires. But as chief technology officer for President Barack Obama's reelection effort, Reed supervised a handpicked team of digital wizards who revolutionized election campaigns.

Throughout history, political parties have collected information on voters to gauge their views and target political messages. But in 2008, the Obama campaign took data mining to a new level by collecting morsels culled from online sources like email, Facebook and Twitter. Then they made history by using these platforms to mobilize supporters. In 2012, Reed's elite geek squad upped the ante by several orders of magnitude in scale and scope. The team built a high-tech platform — code name Narwhal — that mobilized an army of nearly a million volunteers and raised almost a billion dollars, much of it from small donations. It was Narwhal that got out the vote in unprecedented numbers by communicating with individual voters in the most personal of ways. In the end, Narwhal's apps and databases generated and analyzed millions of precious nuggets on voter attitudes and preferences. That enabled the team to get up close with tens of millions of Americans, delivering an unexpectedly lopsided presidential victory that left opponents shell-shocked. As one dejected Romney staffer told reporters, "They targeted voters we didn't even know existed."

Discover caught up with Reed at 1871 (named for the year of the Chicago Fire), a cavernous high-tech incubator in Chicago's Merchandise Mart just north of downtown that is home to 225 start-ups. The soft-spoken, 35-year-old Greeley, Colo., native talked for several hours over the course of two sessions about the ultimate revenge of the nerds.

Discover: How did you go from tech guru to political transformer?

Harper Reed: I had done some volunteer work for Obama in 2008 and I was very much a supporter of the president. A decision was made by the Obama campaign to reach outside of their talent pool and comfort zone, and to hire people who were better at this than they were. So when Michael Slaby [the campaign's chief innovation and integration officer] recruited me, it just seemed like a tremendous opportunity to work on the presidential campaign and to have that experience. Transforming politics wasn't what was important.

D: Was it the technology itself then that was transformative?

HR: I think the real innovation was the team, not the technology, and the decision to bring people in-house from outside of politics. Previous campaigns had mostly outsourced technology to political vendors like Blue State Digital, a tech company that cut its teeth on Howard Dean's [failed presidential] campaign in 2004. In contrast, we brought people in from Google, from Facebook, from Twitter and from companies all around Chicago. We didn't want inventors or visionaries or anyone who was going to make things complicated. We just wanted people to come in, work their hardest, not require us to train them, and to aggressively execute.

D: In 2008, the Obama campaign's use of social media and online tracking tools expanded the Democratic Party's voter data information base by at least tenfold. But much of this information was siloed in separate databases or used a patchwork of software programs that weren't compatible with each other, which made it difficult to access, integrate and leverage the data. When you got involved, how did you break down these barriers?

HR: We spent a lot of time figuring out how to integrate databases that were all over the place. We needed to create a single software platform that would integrate and unify massive amounts of data that had been accumulated since the 2008 campaign — up to hundreds of millions of pieces of data from previous campaigns, from political canvassers, from the Democratic Party's databases on registered voters, from what people posted on their Facebook pages, or how they responded to email solicitations — so that we could easily access and use this information to target voters.

We looked at what we could achieve pretty quickly, from a software perspective, using programs we were already familiar with and which we knew people would use, because we didn't have much time — only 18 months from the time I was hired until the election.

+

We also wanted to use the technology as a force multiplier, in other words, as a tool that made it easier for people to [volunteer and] get involved in the campaign and made it easier for people to vote and made the entire process more efficient. In 2008, I wanted to be involved, but I didn't know how, and when I did volunteer, I spent most of my time [in a field office] manually entering voter information on spreadsheets.

This was important but tedious and inefficient. I wanted to solve that problem and make sure that if you wanted to get involved, that you could do it easily, and the only thing you would need is Internet access. We also wanted to find a way to talk to every person and make sure every person votes — and that includes all 200 million Americans who are eligible to vote.

D: Could you walk me through how you helped to create a grassroots effort that mobilized nearly a million volunteers?

HR: We developed our product called Dashboard, which was a software tool that was designed to be a virtual campaign office to help volunteers communicate and collaborate through emails and interacting online. It was our attempt to take an offline field office and merge it online. This software portal automated recruitment and outreach to campaign volunteers, which is what made possible the deep penetration of the campaign. People could volunteer online and be connected with their neighborhood team based on where they lived.

The Dashboard technology allowed us to empower people to easily get involved in the campaign. Maybe they were in a rural area and couldn't participate through the normal channels. The only thing they needed was Internet access. We were able to give equal access [and equal ability] to participate in the campaign to my mom in Colorado, to a blue-collar worker in Virginia, to a white-collar worker in Florida. It even allowed a guy in a hospital to participate in the campaign without leaving his hospital bed.

D: Dashboard had several menu options, like "my team," "my messages," "resources," "numbers" or "events." So people could just log on, click on what they needed, and then get their personalized instructions at home rather than volunteering at a campaign field office.

HR: The Call Tool [an app that's part of Dashboard], for example, allowed thousands of volunteers to do phone canvassing from their home and pull up lists of people to call and a script that said, "Hey, call Linda. This is her number. This is where she lives. Here's a script to read when you get on the phone." And I like to think all of these people with iPads or Android devices or cell phones were able to use this and interact with it without leaving their house.

[During the campaign], there was this picture of [U.S. Rep.] Debbie Wasserman Schultz (D-Fla.) using her iPad to use the Call Tool. And she can do that on a bus. She has a lot of technology in her hands. She can use lists [to make calls], and she can do this without leaving her house and having to go somewhere.

Dashboard also handled some of the metrics of the grassroots part of the campaign by tracking activities like phone calls to voters, voter registration or canvassing. The software allowed volunteers to quantify their work, to track how much they've done, to see if they're hitting their goals and to share best practices, tips and tricks. Then, they were able to participate, like call Nevada or knock on doors in Colorado. It was an attempt on our side to create a gateway to allow people to get into the offline world because you are much more productive if you actually go out. Dashboard was about empowering that community.

It also had a social networking application, sort of like Facebook, so that people could connect with other people in their neighborhood teams or their team leaders, and interact, like soliciting rides to events, that type of thing. The goal here was to allow people to organize in their neighborhoods where they are most comfortable, and work and meet with their peers and their neighbors.

I live in an urban community, and I don't know my neighbors. Even though I built it, I would join in, and I saw people from the neighborhood, people I saw on the train, and you feel better when you know you're not alone. And having all these people around, you're able to say, "Oh, my neighbor over here across the street is also working on the campaign and helping out." That's really neat. We were able to get more people involved, to get out the vote, to get people out to go knock on doors.

D: The campaign also microtargeted voters by firing off emails or posting messages on Facebook that were shaped to appeal to their particular interests or causes using tracking software, similar to ones used by online retailers to craft ads. Is that how you were able to tailor political messaging to such a degree?

HR: The most important thing we did was listen. People forget to listen. We would watch and see what is important for people. What are people talking about right now? You don't need a software platform to do this. You can just watch what your friends are doing.

D: But you were watching what millions of your friends were doing.

HR: Yeah, there's a scale here. But even if you're talking about your regional Planned Parenthood, they would have a regional page, and they can see the activity and people's updates, which would give them a pretty good idea of what's happening and enable them to respond.

D: But when people donated to BarackObama.com, the campaign asked to harvest some of their Facebook data, which meant you had the names at least of their Facebook friends. Or you knew if they responded to Facebook postings or targeted email solicitations about specific issues. Every time someone "liked" Planned Parenthood on Facebook, it registered with the Obama campaign. How was this information used?

HR: We also did it on Twitter, on Tumblr and even on Pinterest. We didn't know everything you were doing on Facebook. But if you shared something or uploaded a picture and tagged it as public, we could look to see what it says.

We knew if someone was interested in health care or reproductive rights based on an Internet interaction on Facebook or a response to an email. Essentially, we used the technology to make sure you're the right person to receive a particular message. Then we'd ask people if they wanted to share this message. We'd look through his or her friends and ask, "Who are the most important people for us to share this with?" And from there, we would share with these people, which continually built our base. So if you were sharing something from the campaign, it would register on Facebook.

And with the content creation, and the postings, we tried to measure things. When you post this, what kind of clicks do you get? On Tumblr, how many re-blogs, or on Twitter, how many retweets? So if you go to our

+

Facebook page, you can see the response to postings. One that got posted about an hour ago already has 54,000 likes, and 3,000 people shared it. This way, we know which messages are the most effective.

Daniel X. O'Neil

D: On election day, campaign workers used a smartphone app called Gordon — named for the man who reputedly killed Harry Houdini — that allowed them to monitor who had already voted, and that helped get out the vote. People even reported receiving emails that asked them to call friends in battleground states who hadn't voted yet. How did you achieve this depth of penetration?

HR: Well, you have poll watchers, and you report that data in; whether you use our mobile app or you use paper, it goes to the field office. They fill it all out, hit submit, and it goes back to us [at campaign headquarters], so we can then start pulling out the data and continually refresh lists of people who have already voted in real time on election day.

And we know who hasn't voted based on the voter registration files. Say [a watcher] is at the polls, and he says Harper has voted, so I get checked off. Then when someone logs in, we can look up their friends from Facebook and see if they voted. So then it's just about ordering it by state. Instead of looking at all of their friends, we just look at the friends that live in the battleground states. And if they haven't voted yet, we'll just ping them and say, "Hey, why don't you call these people?" We sent a lot of these — maybe around 7 million.

D: Your campaign techniques raise serious privacy issues. How do you know so much about each and every voter?

HR: That's a tough topic, and I think it was unfairly blown up for the campaign. You're talking about "violations," but we all agreed to participate in this world. When you use Facebook or Amazon, you agree to their terms of service and their data usage. And as a consumer, you can always not use it.

It's the same with the campaign. We used publicly available data, such as information from voter registration files, and what was reported to the campaign by people canvassing their neighborhoods, as well as information posted on Facebook and what was given in response to email requests.

There's a new world of information management out there. People are building apps that are doing super-crazy things, and there's a lot of talk about modeling and microtargeting. Facebook can predict when people are going to break up, and Target is able to predict if a woman is pregnant before she knows just based on the type of lotion she bought. What we were able to predict — based on voter registration and campaign canvassing — is that if you knocked on someone's door, that person probably wasn't a Republican.

D: You don't think we're on a slippery slope with the campaign collecting all this data, leading toward a Big Brother type of world?

HR: No more than we are with Target or Facebook or Amazon or anyone else — a lot of companies are doing the same thing. And it's important to be clear that a campaign isn't just the government. That said, we have to be careful, and we can't just assume it's going to be OK. But I honestly don't think that it is as big an issue as I think a lot of people think it is.

D: You don't have trouble posting personal things online, like your weight, what you ate for dinner last night or lists of your favorite books — a very eclectic mix, ranging from heavy-duty sci-fi to Alan Greenspan, Ayn Rand, Kurt Vonnegut, Haruki Murakami and Barack Obama. It's almost like a life lived online.

HR: There's this old idea of "digital natives" where there are these people who are born into technology, and then others who aren't. But I think now just about everyone is a native. The few people who aren't are older and are usually people who have resisted going into this world. But even they are using computers.

What I do think is important is this idea of a "privacy native" where you grow up in a world where the values of privacy are very different. So it's not that I'm against privacy but that the values around privacy are very different for me and for people who are younger than my parent's generation, for whom it's weird to live in a glass house. But my 16-year-old cousin posts anything and everything on Facebook — it's just a different way of consuming privacy.

D: You think this debate is generational?

HR: I think it is, and this whole controversy about privacy being eroded on the Internet sounds like old people talking to young people about rock 'n' roll. Like society is going to fall apart. But the notion of privacy is different for people younger than 25 who grew up with Facebook their entire life. They have much more nuance and much more controlled interaction with their data than people who are older. So they do things like deactivate their Facebook accounts, or use things like Snapchat, where their content erodes. Yes, the old style of privacy is gone — but so is riding horses.

D: But what about the recent NSA/PRISM projects? The U.S. government, through the FBI an

the NSA, was collecting call log data from millions of Verizon customers. It also was mining the servers of big tech companies such as Google, Facebook, Skype and Yahoo, collecting emails, videos, photos, social network profiles and even doing live surveillance of someone doing a Google search, as part of the war on terrorism.

HR: The first thing is — and this is very important — I support the unmonitored use of the Internet for everyone. It doesn't matter what country you're in or what you do for a living — everyone should have the right to an unmonitored Internet.

Obviously, I support the president, but we need to make sure we're not sacrificing our freedom. We need more transparency and more insight into what's happening, and we can agree that what's happening is the right balance between stopping terrorism and having the freedom to have an unmonitored Internet, and making sure we're not searched with every click on the Internet.

D: Do you think this will trigger a privacy backlash that will affect data mining in the next election?

HR: This has very little to do with data mining and more to do with the fact that it is unrestricted, secret and not transparent. We very often participate in programs where we give up data in trade for something else. I got my retina scanned so I can go through the airport faster when I travel, for instance, or we go on Facebook to share photos. The problem with this is that it is completely secret, and none of us have a choice as to whether we can opt in to it.

[This article originally appeared in print as "Harper Reed: Game Changer."]

FROM THE DECEMBER 2013 ISSUE

Trip Wire: Q&A with Epidemiologist Stephen Morse

Stephen Morse is in the vanguard of an effort to predict the next pandemic — but says prevention is an elusive goal.

By Gemma Tarlach | Friday, November 01, 2013

RELATED TAGS: VIRUSES, INFECTIOUS DISEASES

Yana Paskova

Quick with a smile and even faster with a pun, native New Yorker Stephen Morse doesn't seem like a man preoccupied with mass killers.

As a boy he toyed with the idea of becoming an Egyptologist or herpetologist — "I spent a lot of time trying to catch snakes in the Pine Barrens of New Jersey" — but eventually he chose microbiology. A lifelong lover of solving puzzles, Morse gravitated toward some of the most mysterious microbes: killer viruses that seemed to strike from out of nowhere, sometimes reaching pandemic levels.

"I like intellectual challenges — that's probably my greatest weakness," jokes Morse, sitting in his office at Columbia University's Mailman School of Public Health, where books, often two or three rows deep, are crammed floor to ceiling.

Morse is credited with creating the term *emerging infectious diseases* in the late 1980s to explain viruses that can exist for years in an animal host without causing illness. The virus "emerges" when human activity, such as habitat destruction, causes host-human contact. With the right conditions — including transmissibility — the virus infects and spreads through our species, sometimes globally.

More than 20 years after he began trying to solve one of epidemiology's biggest challenges — understanding why pandemics happen and how we can stop them — Morse serves as the director of the U.S. Agency for International Development's worldwide PREDICT project, which has been part of the organization's Emerging Pandemic Threat (EPT) initiative since 2009. The program is multidimensional, from cutting-edge mathematical virus modeling to field educators teaching hunters how to reduce risk of infection from contaminated game.

On a humid New York summer day, in between fielding calls from the State Department and other eminent virologists about expanding PREDICT's efforts into new countries, Morse explained to *Discover* why preventing pandemic remains an elusive goal.

Discover: Influenza is the biggest pandemic threat we face. Does the threat come from known strains evolving to be more virulent or from the emergence of a strain that's never been seen before?

Stephen Morse: When I suggested influenza in 1990 as a paradigm of an emerging infection, (Nobel laureate) Howard Temin, a mentor of mine, disagreed. He believed it was a question of evolution, as did most microbiologists. But I think it's a prototype in many ways. It's fooled us every single time. It's very complex. It has multiple hosts and can evolve by mutation but also reassortment (when two closely related strains infect the same host and exchange gene segments, producing new strains — a process distinct from mutation, when the RNA of a virus is miscoded during replication). We're often unaware of what it's doing in nature.

What is the mechanism for the critical step between evolving in nature and spilling over into humans, causing infection? Take us through, for example, H5N1, avian influenza A, commonly known as bird flu, which has been a problem particularly in Asia for the past decade.

SM: With H5N1, in the late '90s there was a small outbreak of 18 cases with six deaths in Hong Kong. That's a high mortality rate, but no one paid much attention; it was not a big deal at the time. They cleared out the markets and the wild birds and the parks, and nothing more was heard.

But the virus didn't go away. It simply went underground, continuing to evolve in its natural host, wild waterfowl. Then it came back in 2003 and it was nasty, so evolved that a lot of people didn't recognize it. It was far more virulent. It had been evolving during that period in its natural hosts.

It was certainly taking its toll on the poultry population. But we weren't seeing a lot of human-to-human transmission, so we didn't see much occasion for H5N1 to go further and take wing, pardon the pun.

Why do China and other parts of East Asia seem to be such an epicenter of influenza? Pigs are considered an ideal influenza "mixing vessel" because they are susceptible to both mammalian- and avian-based strains of influenza. And wild waterfowl, particularly migratory species, often host multiple strains of avian influenza. Is the prevalence of outbreak in Asia due to the number of animals on the continent or something else?

+

SM: Lewis Thomas, in *Lives of a Cell*, has an essay on germs that says something to the effect that all of these events are an unfinished negotiation over boundaries between the host and the pathogen. That's really what it is. The boundaries have been set over many years, many generations with the pathogen's natural host. We haven't reached that degree of armistice.

When you put several species together, quail and ducks or chickens and ducks, there are opportunities for species that never get together in nature to suddenly be in close proximity and share their viruses. In its natural hosts, influenza appears to be relatively static, but when it gets into a new host, many of those constraints are lifted. It's a renegotiation. Why do these pandemics come from China? Because China has integrated farming systems. They put two of influenza's favorite hosts, waterfowl and pigs, together.

Is H7N9, identified earlier this year, a virus with real pandemic potential?

SM: I'm more concerned about H7N9 than I was about H5N1. H7N9 is very recently evolved. H7 has been around a while — people get conjunctivitis with it but don't even know they had influenza. But N9 is new. It's very rare in nature. N9 seems to have come from a wild bird, probably around Korea somewhere, although there's evidence for rare N9s in other birds in Mongolia and Siberia, where these migratory wildfowl tend to congregate. H7N9 has to get deep into the lungs, which is why it's not that transmissible.

If it's not very transmissible, why does it worry you? Granted, a virus could always become more transmissible either through appropriating a piece of genetic code from a more easily spread strain (reassortment) or through its own genetic code mutating. But that risk exists for any virus. Why is H7N9 such a threat?

SM: In humans, the normal influenza receptors we have in the upper respiratory tract are not like the avian receptors H7N9 needs. It has to go deeper down, into our lower respiratory tract, to find the receptors it needs. Because it has to go deeper, once it does infect, the prognosis is not good — the risk of mortality would be high. Unlike H5N1, H7N9 could be as bad as the 1918 influenza pandemic if it were to become as transmissible because it's unfamiliar to humans — we've never seen it before — and because of how deep down our receptors for it are.

The track record for predicting a pandemic is, well, zero. Why?

SM: It's true we've never predicted pandemic successfully. That's been our biggest failure. We have a very bad handle on how it adapts to humans. We have very poor ability to predict transmissibility.

H5N1 can bind to human receptors, for example, but H5N1 proved receptor specificity is not enough to be highly transmissible. It's a necessary but not sufficient condition. The question is what are the sufficient conditions to transmit person-to-person. The answer is we still cannot predict that. We can get the complete genetic sequence of a virus, but nobody can tell you whether it's going to be able to transmit. They can tell you, possibly, whether it has the capability of infecting humans, but that's not the whole story.

Why do viruses cause severe disease in us? It's very likely the hyperinflammatory response, the overabundance of what people call the cytokine storm, which causes many of the symptoms. They're the same symptoms you

+

see in septic shock and other types of severe inflammatory reaction, an over-exuberant response from our own protective mechanisms. We know some of the molecular features that cause these reactions, but we don't know all of them.

Since its start in 2009, PREDICT has been working with its partners to map hot spots where pathogens are most likely to emerge in human populations and cause infections, with the potential to escalate to a pandemic. These kinds of maps have been attempted before, but how does this type of predictive mapping inform our understanding of, say, a particular strain of influenza?

SM: We need to add to our knowledge of disease ecology, of knowing what's out there. Looking back, I don't think if we saw the precursor, the ancestor, of HIV, we would have recognized the threat it posed until it reached the human population. I don't have any illusions that finding something in nature will predict the next pandemic. But we need to build our database. We don't have any way to do a reasonable risk assessment.

You make an interesting point that, even if we'd had the surveillance in place, we might not have appreciated the threat HIV or its precursor posed. Why?

SM: You wouldn't think HIV would have succeeded because it's so inefficient at transmission. But HIV took advantage of contaminated injection equipment, of sexual activity. Transmissibility depends on our behavior. HIV might not have happened 100 years ago.

Another big part of PREDICT's mission is, in fact, to address human behavior that might give a virus an advantage. Is public health education more important than the cutting-edge pathogen detection done in labs to prevent pandemic?

SM: The lab is very important. Certainly it's an essential part of what we do as scientists. But if we want to do anything about emerging infections, we have to do it as a public health and policy issue. There are a lot of ways to do it. They may not all be economically feasible. But a lot of it is appropriate behavior change, such as safe hunting: The original cases of infection of what is now HIV obviously got into somebody's bloodstream. You see people cutting the game up, having cuts on their hands. Eventually, something's going to happen.

Do you think we'll ever be successful in predicting a pandemic?

SM: I'm an optimist in that I see movement. The fact that we can have a USAID program like Emerging Pandemic Threats, and that the Centers for Disease Control and Prevention is strengthening its global surveillance efforts and field epidemiology training programs, these are very important, as are communications — when I was starting out in this field, who would have believed you could reach almost anywhere in the world with a cell phone?

Having global surveillance is the first step and a necessary step, but it's not sufficient. What we would like to do is find the rules for these emerging infections, the rules for viral traffic. We already know something about those, how they get into human population. But now we need to know the proclivity of a virus or other pathogen to get into the human population.

+

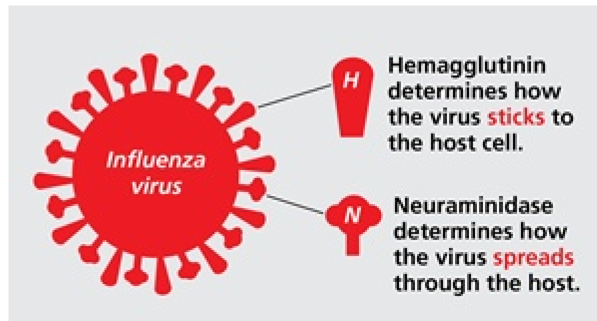
The One Health Initiative (a global partnership between physicians, veterinarians and public health officials) is also an important part of it. People are beginning to realize all of the species on this Earth have something in common. Everything has a common thread. You know, I like the idea of finding commonalities, of order in what seems to be a chaotic system. A virus is not just an animal problem, and it's not just a human problem.

As someone who's been at the forefront of unraveling emerging infectious diseases and the mechanisms of pandemics, what keeps you up at night?

SM: Most of all, the one we're not expecting. Because none of these pandemics have been predicted. I worry about H7N9. I worry about the new coronavirus. But what I really worry about is the one that's out there that we're not aware of, and we're not looking for.

The Name Game: Figuring Out Flu

Keeping track of influenza's many names (and many strains) sometimes seems as tricky as predicting a pandemic. Here's what you need to know.



Alison Mackey/Discover

ABC, easy as 1-2-3

Influenza viruses belong to the *Orthomyxoviridae* family and are divided into A, B and C types based on their antigen (antibody-producing) protein type. Types B and C are found in humans and, occasionally, seals and pigs, and are not divided into subtypes. Type A shows up in birds and mammals like us, and is the only type of influenza that has caused pandemics. It's influenza A subtypes that typically pose a health threat.

What subtype surfaces

Influenza A is further divided into subtypes based on how it binds to the cell of its host. A glycoprotein on the virus's surface called hemagglutinin, which has 17 identified types (H1-H17), determines how the virus sticks to and enters the host cell.

Another glycoprotein, neuraminidase, with 10 known types (N1-N10), affects how efficiently the virus spreads through an infected individual. It is the specific combination of glycoproteins that distinguishes one subtype from the next (H7N9 versus H5N1, for example). Not all potential host species are equally susceptible to all glycoproteins, so some subtypes infect one species, such as chickens, but not others.

For the birds

The term *bird flu* is imprecise. More than 100 species of wild waterfowl have been identified as natural, usually asymptomatic hosts of a variety of avian influenza A (bird flu) subtypes. Influenza A subtypes H5N1 and H7N9, for example, are both called bird flu, though the viruses have different paths of infection, or receptors, and different degrees of transmissibility.

When flu piggybacks

Swine flu applies to any type or subtype of influenza for which pigs are natural hosts. It is most often associated with the H1N1 subtype, which was behind the 1976 swine flu scare. In 2009, a new strain of H1N1 caused what the Centers for Disease Control and Prevention called "the first influenza pandemic in more than 40 years," testament to a long-known influenza subtype evolving into a new threat.

No flu for you

Other pathogens with pandemic potential are sometimes mistakenly called "flu," including SARS and MERS, two coronaviruses that emerged in 2003 and 2012, respectively. Both coronaviruses cause respiratory symptoms similar to influenza.

The 3 R's of Influenza Pandemic

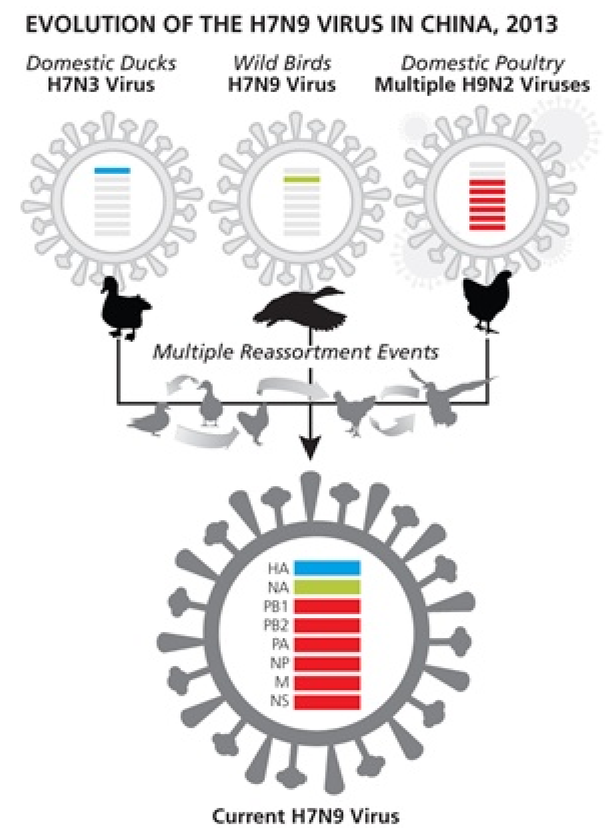
There are several steps between an influenza strain's emergence from its natural animal host and a large-scale human outbreak. Here are three important links in the possible chain of events.

Step 1: Rapid evolution

Influenza has a high rate of mutation because enzymes involved in RNA replication lack a proofreading function, leading to frequent errors. Some of the mutations increase a strain's pandemic potential. For example, the infamous 1918 influenza may have been the second wave of a strain that appeared in 1917. The 1917 virus had infection and mortality rates typical of seasonal flu, but a single mutation in the proteins affecting how the virus binds to a host cell may have led to the deadly 1918 wave, which killed more than 50 million people worldwide.

Step 2: Reassortment

When multiple influenza subtypes come into close contact in an environment such as a farm, the viruses can exchange pieces of genetic code. This viral swap meet, called reassortment, can increase transmissibility and virulence. The 2009 H1N1 strain, which killed more than 4,000 people worldwide, incorporated pieces of avian, human and swine flu subtypes through reassortment.



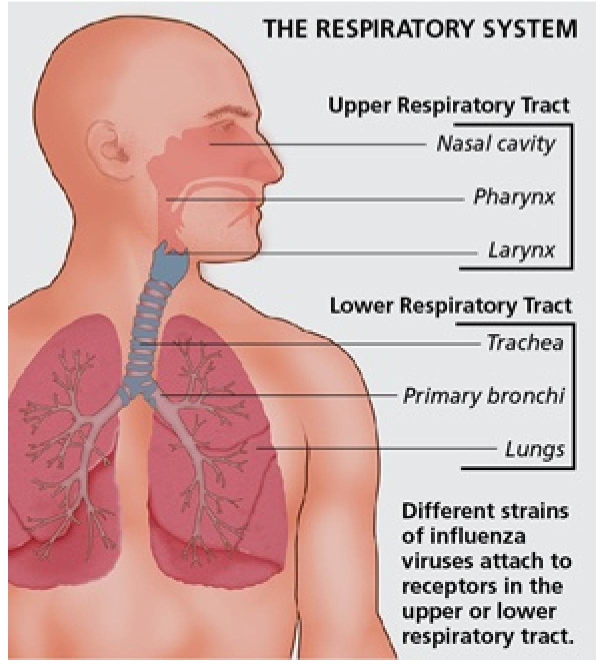
H7N9 is an example of a virus making proteins from "borrowed" RNA segments acquired during reassortment with other influenza subtypes that are found in different host species.

Alison Mackey/Discover based on illustrations courtesy of the CDC/Dan Higgins

Step 3: Receptor specificity

Like different picks in a locksmith's tool, the 17 known subtypes of hemagglutinin, a surface protein on influenza strains, match different sialic acid receptors on a host cell. Without the right receptor, the virus cannot attach tightly enough to invade the cell and co-opt it for replication.

Generally speaking, humans have upper and lower respiratory receptors. Some influenza viruses attach to upper respiratory receptors. These generally are more transmissible human-to-human because the virus doesn't have that far to travel along the respiratory tract to find the cell it needs for replication. Other influenza subtypes must travel to the lower respiratory tract to find their receptors; while this generally makes a subtype less transmissible, infection via these receptors often is associated with higher mortality.



Science Source

The Rogues' Gallery of Potential Pandemics

The most dangerous virus is the one we haven't yet encountered, but epidemiologists already have their eyes on several ne'er-do-well pathogens.

H7N9

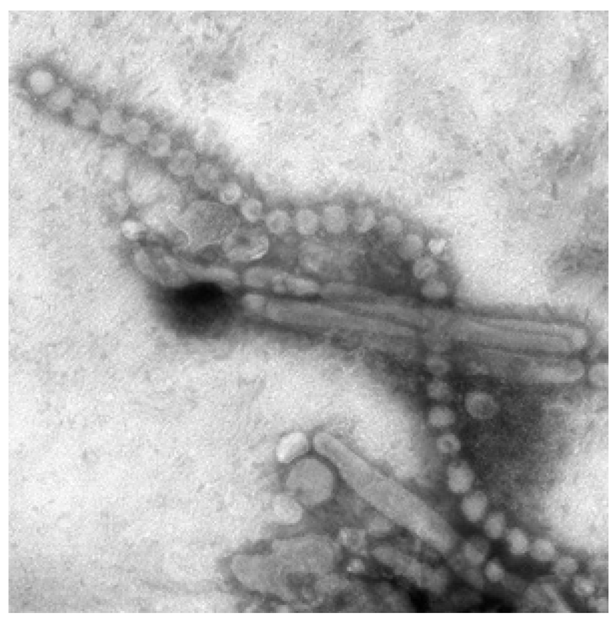
Known associates: Similar influenza H7 subtypes, some of which cause conjunctivitis (pinkeye) but not typical flu symptoms; N9 subtypes are novel to humans.

Aliases: avian influenza A, bird flu

First offense: Identified in April, H7N9 appears to have spread from wild waterfowl host to poultry in China and, from there, to humans.

Favorite hangouts: Flourishes among birds in crowded farm and market environments.

Modus operandi: About a third of the 130 people infected with H7N9 earlier this year died; the pace of new

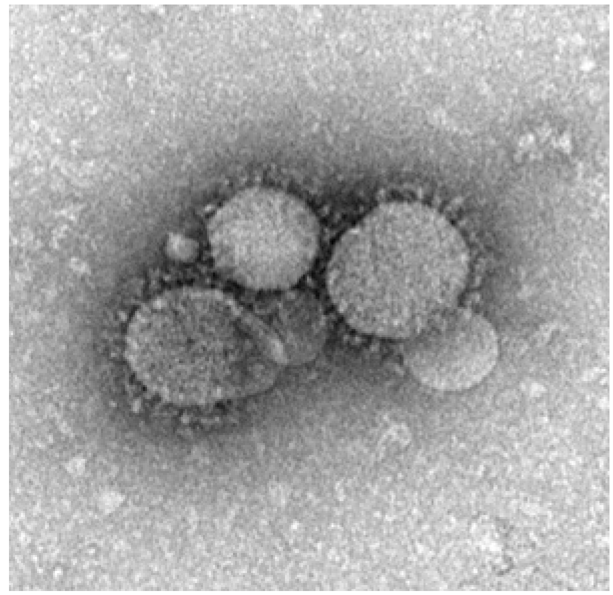


CDC/Cynthia Goldsmith and Thomas Rowe

cases fell sharply after the Chinese government took steps to reduce bird-to-human transmission opportunities.

Threat level: HIGH. H7 subtypes in general can become more transmissible to humans, but the N9 element of H7N9 is newly evolved, and, if it became more transmissible, humans would have no pre-existing immunity to it. In addition, H7N9 may have rapidly acquired resistance to existing antiviral medication.

MERS-CoV



CDC/Maureen Metcalfe and Azaibi Tamin

Known associates: Fellow coronavirus SARS-CoV (see below) and other members of the Coronaviridae family.

Aliases: Middle East Respiratory Syndrome

First offense: Identified in humans in 2012 in Saudi Arabia; other cases found in the Arabian Peninsula or in individuals with connections to the region.

Favorite hangouts: Earlier this year, researchers found an Egyptian tomb bat in Saudi Arabia with a strain of the virus identical to that of the first human patient; another team discovered that 50 camels from the area all tested positive for MERS-CoV antibodies, suggesting camels may be intermediary hosts.

Modus operandi: Like SARS, MERS-CoV causes difficulty breathing, coughing and fever, and can progress to pneumonia and respiratory failure.

Threat level: MODERATE. As of September, 132 cases of MERS-CoV had been confirmed, with 58 deaths, suggesting high virulence. Milder cases may have gone unreported, increasing the number of infections but lowering the mortality rate. In July, after an Emergency Committee meeting, WHO declared MERS-CoV was not an imminent public health crisis.

SARS-CoV

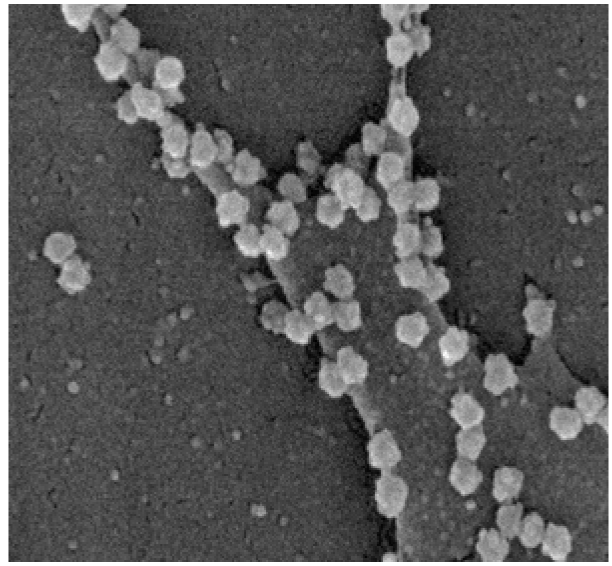
Known associates: A member of the Coronaviridae family, which includes pathogens behind the common cold and a highly contagious intestinal disease that infects dogs.

Aliases: SARS-associated coronavirus, severe acute respiratory syndrome

First offense: Identified in 2003 in China, it likely emerged from an as-yet-unidentified small mammal.

+

Favorite hangouts: The virus appears to have retreated to its natural reservoir, laying low, in effect, until another human-host interaction allows it to re-emerge.



CDC/Dr. Mary Ng Mah Lee

Modus operandi: Symptoms such as coughing and difficulty breathing begin two to 10 days after infection, though individuals may be contagious before or after showing symptoms. The general mortality rate is roughly 10 percent, but climbs to 50 percent in individuals with other health problems.

Threat level: MODERATE-HIGH. It's been 10 years since the outbreak that infected an estimated 8,000 people worldwide and killed at least 750. Due to its high transmissibility and moderately high mortality rate, in 2012 SARS-CoV was designated a potential "severe threat" by the CDC's National Select Agent Registry.

H5N1

CDC/Cynthia Goldsmith and Jackie Katz

Aliases: Avian influenza A, bird flu, Highly Pathogenic Avian Influenza H5N1 (HPAI H5N1)

First offense: A small outbreak in Hong Kong in 1997. Returned in a deadlier form in 2003, infecting more than 600 people, mostly in East Asia.

Favorite hangouts: H5N1, which evolved in wild waterfowl, has devastated domestic poultry with a 90 to 100 percent mortality rate.

Modus operandi: WHO estimates that 60 percent of individuals infected with the virus will die, a rate on par with the Black Death and other public health catastrophes. (The 1918 Influenza Pandemic had an estimated mortality rate of less than 5 percent.)

Threat level: MODERATE-HIGH. Although it has a high mortality rate, H5N1 is not easily transmissible between humans. Scientists are watching closely for signs of mutation or reassortment — a process in which various strains can mix and match their genetic material — that may make it spread more efficiently.

H1N1

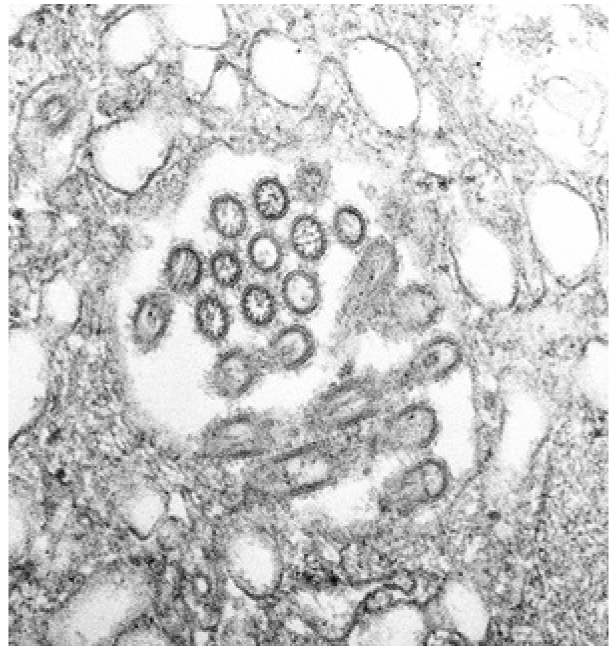
+

Known associates: Other influenza A subtypes that naturally reside in pigs.

Aliases: Swine flu, swine influenza A

First offense: H1N1 made headlines in the ‘70s; a new and more deadly strain of the virus subtype emerged in 2009. Lab-confirmed H1N1 deaths during the 2009-’10 pandemic were roughly 18,500 worldwide, though some theorize the mortality rate was substantially higher.

Favorite hangouts: H1N1’s evolution is a classic example of its natural reservoir, the pig, serving as a mixing vessel. Pigs have multiple influenza receptors and can harbor human and avian strains of the virus in addition to their own, leading to reassortment. The 2009 strain of H1N1 is, in fact, a hodgepodge of swine, human and avian strains of the virus.



CDC/Cynthia Goldsmith and D. Rollin

Modus operandi: The 2009 H1N1 strain is worrisome because, like the 1918 influenza, it appeared to be more lethal in young adults than most influenza strains.

Threat level: MODERATE-HIGH. The 2009 H1N1 strain is expected to remain in worldwide circulation; because it is no longer a novel strain, however, many individuals will have some immunity to it.

H3N2v

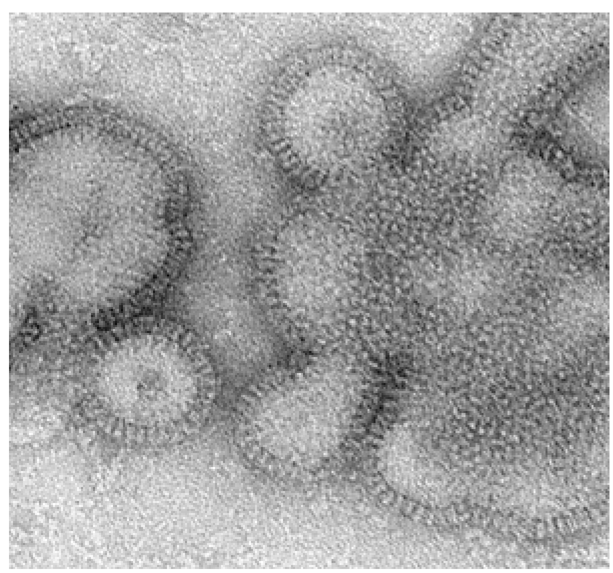
Known associates: Other subtypes of swine flu

Aliases: Swine flu variant (the word *variant* applies to influenza A subtypes that usually only infect pigs if they go on to infect humans.)

First offense: Identified in pigs in 2010, H3N2v began infecting humans in the American Midwest a year later.

Favorite hangouts: Farms and agricultural shows and fairs

Modus operandi: Since 2011, more than 300 people have been infected with H3N2v, with one documented case of human-to-human transmission.



CDC/ Dr. Michael Shaw and Doug Jordan, M.A.

+

Threat level: LOW. Although outbreaks have been sporadic and almost entirely limited to individuals in close contact with swine, H3N2v is considered enough of a potential threat to be targeted in the development of this season's flu shot.

FROM THE MARCH 2014 ISSUE

Mutation, Not Natural Selection, Drives Evolution

Molecular evolutionary biologist Masatoshi Nei says Darwin never proved natural selection is the driving force of evolution — because it isn't.

By Gemma Tarlach | Sunday, March 16, 2014

RELATED TAGS: EVOLUTION, GENETICS

Masatoshi Nei expands on his evolution-busting theory in his 2013 book *Mutation-Driven Evolution.*

Michael Ray

In a cavernous concert hall, before an eager audience of thousands, Masatoshi Nei is experiencing a technical glitch.

The biologist has just received Japan's prestigious Kyoto Prize in Basic Sciences, honoring his groundbreaking exploration of evolution on a molecular level. The eyes and ears of international media, diplomats and dignitaries, including Japan's Princess Takamado, are trained on the soft-spoken 82-year-old as he delivers his acceptance speech.Or tries to. On a massive screen above him, a slide show advances and retreats randomly as Nei attempts to present techniques he pioneered that have revolutionized his field — and theories that challenge some of its most deeply rooted ideas.

"So sorry," Nei tells his audience with an endearing chuckle. "I'm always pursuing the theory, not the practical."

Practicality has been, however, a guiding force throughout Nei's career, from his early agricultural research to his decades-long quest to move evolutionary biology away from subjective field observations and into objective, math-based analysis on a molecular level. In 1972, he devised a now widely used formula, Nei's standard genetic distance, which compares key genes of different populations to estimate how long ago the groups diverged. In the early '90s, Nei was a co-developer of free software that creates evolutionary trees based on genetic data. Two decades later, Molecular Evolutionary Genetics Analysis, or MEGA, remains one of the most widely used and cited computer programs in biology.

But it's his natural selection-busting theory, which Nei developed in the '80s and expanded on in the 2013 book Mutation-Driven Evolution, that the researcher wants to see embraced, cited and taught in schools.

A few days after his presentation slides finally cooperated, Nei, director of the Institute of Molecular Evolutionary Genetics at Pennsylvania State University, spoke with Discover about where he believes Darwin went wrong.

Discover: You began your academic career in Japan in the '50s as an assistant professor of agricultural science. How did you, no pun intended, evolve into a molecular biologist taking on Darwin?

Masatoshi Nei: I wanted to make population genetics useful and practical, so I went into plant breeding. But I started to ask, why does phenotopic [observable trait-based] evolution take place? I was interested in it on a genetic level. Charles Darwin said evolution occurs by natural selection in the presence of continuous variation, but he never proved the occurrence of natural selection in nature. He argued that, but he didn't present strong evidence.

But among the people working on evolution, most of them still believe natural selection is the driving force.

If you say evolution occurs by natural selection, it looks scientific compared with saying God created everything. Now they say natural selection created everything, but they don't explain how. If it's science, you have to explain every step. That's why I was unhappy. Just a replacement of God with natural selection doesn't change very much. You have to explain how.

OK, so, explain how.

MN: Every part of our body is controlled by molecules, so you have to explain on a molecular level. That is the real mechanism of evolution, how molecules change. They change through mutation. Mutation means a change in DNA through, for example, substitution or insertion [of nucleotides]. First you have to have change, and then natural selection may operate or may not operate. I say mutation is the most important, driving force of evolution. Natural selection occurs sometimes, of course, because some types of variations are better than others, but mutation created the different types. Natural selection is secondary.

Nei makes a case for mutation-driven evolution at the 2013 Kyoto Prize awards ceremony.

The Inamori Foundation

Someone on the outside looking in at the debate might say you and other researchers are splitting hairs, that both mutation and natural selection drive evolution. How do you respond?

MN: I don't study the character or the function; I study the gene that controls it. My position is mutation creates variation, then natural selection may or may not operate, it may or may not choose the good variation and eliminate the bad one, but natural selection is not the driving force.

In neo-Darwinism, evolution is a process of increasing fitness [in the sense of an organism's ability both to survive and to reproduce]. In mutation-driven evolutionary theory, evolution is a process of increasing or decreasing an organism's complexity. We tend to believe natural selection selects one type. But there are many types, and still they're OK. They can survive, no problem.

For example, if blue eyes are better for some reason in Scandinavia, that mutation has a selected advantage, and then of course that advantage will occur more in that population. But first you have to have the mutation. And natural selection itself is not so clear. In certain cases it is, but not always. The gene frequency of blue eyes may have increased by chance, too, rather than natural selection. The blue eye color may be just as good as green. Both can see.

In 1968, your friend and mentor Motoo Kimura proposed the neutral theory of molecular evolution, arguing that most mutations that occur have neither advantageous nor deleterious consequences for an organism. How did you take neutral theory a step further with mutation-driven evolutionary theory?

MN: Kimura believed morphology [appearance] evolves through natural selection. He applied neutral theory only on a molecular level. I say it can determine morphological characteristics as well because DNA determines everything, but to prove this has not been so easy. [Laughs.] Forty or 50 years later, I am still trying to prove it.

One of your most significant contributions to the field is Nei's standard genetic distance, a formula that determines when different populations diverged based on mathematical analysis of their genomes. But this formula assumes the rate of genetic change is constant. Do you think human activity — from overfishing to burning fossil fuels to illuminating our cities and highways with artificial light — could be speeding up the rate of mutation?

MN: I think there is a mutagenic element to human activity, but it's difficult to gather proof. It's occurred only in, say, the past 10,000 years, and I don't know if it's changing the rate of mutation. You can identify how many different mutations occurred, but not always how.

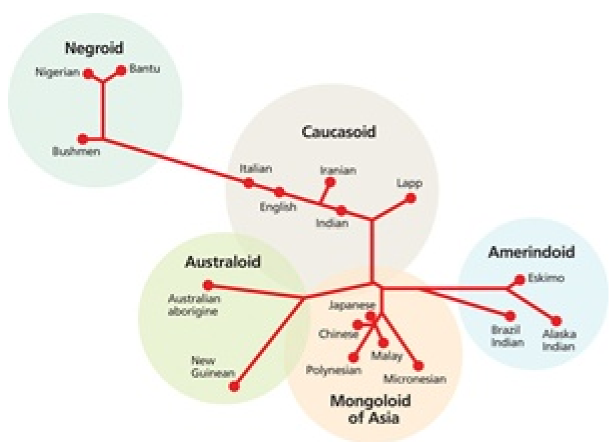
You've been talking about mutation-driven evolution for more than three decades. Why do you think the majority of evolutionary biologists remain in the natural selection camp?

+

MN: I expressed this simple view first in 1975 in my book *Molecular Population Genetics and Evolution*, and in 1987 in a chapter in another book, but no one changed their views or the textbooks. Of course, at that time, molecular biology had not developed too far yet, and traditional evolutionary biology only considered morphology, not how the variation occurred.

Some birds, for example, have a variant of hemoglobin that allows them to fly over the Himalayas, at very high altitudes. Some alligators have a different variant of hemoglobin that allows them to stay submerged for a very long time. This has been known for a while and everyone felt, well, variation exists in the populations, but the condition necessary must be just natural selection.

In 1987, you co-authored a paper with Naruya Saitou describing the neighbor-joining method, a novel algorithm for creating evolutionary trees by working backward based on key genetic differences between related species, the idea being the more recently one species diverged from another, the more similar their DNA will be. It's been cited more than 34,000 times over the years and has become a cornerstone of molecular evolutionary biology research. Why do you feel it was so influential?



The neighbor-joining method allows scientists to calculate when different species, or variations within a species, diverged by analyzing differences on a molecular level. Based on a 2002 study, this illustration maps the relationships between 18 human populations, using the neighbor-joining method to create an evolutionary tree built on genetic data.

Alison Mackey/Discover after Jason Spatola via Wikimedia Commons

MN: It's simple. [Laughs.] I had developed the genetic distance theory [in the '70s] because I wanted to make a phylogenetic tree, and distance can be used for making trees. But I was also interested in statistics. So I combined the two methods. To test it, first we did computer simulations: We generated a DNA sequence for an evolutionary tree where we already knew where the tree branched. Then we used statistics, the neighbor-joining method, to reconstruct the tree and test whether it resembled the actual phylogenetic tree. It did, and that's how we knew this method gave a pretty good idea of how species evolved and diverged.

At first, other biologists were fanaticists about sticking to earlier methods of calculating relationships between species. There were a lot of stupid fights in the '80s, but I insisted it would work. In the case of, say, using 100 genetic sequences, we can make a neighbor-joining tree within a few seconds. With the regular method, it would take months. And after working for months, the result was almost always the same as the neighbor-joining method.

You've stated on a number of occasions that you're ready for a lot of criticism over your most recent book, 2013's *Mutation-Driven Evolution*. Why?

MN: I presented such views in my 1987 book *Molecular Evolutionary Genetics*, but people didn't pay attention. Textbooks on evolution haven't changed: They still say natural selection causes evolution. My views were totally ignored. In that book, I discussed many statistical techniques, and only in the last chapter did I discuss the problem of natural selection not being proven. The chapter did not convince a lot of people, I thi because they already had a preconceived notion that natural selection must be the driving force because Darwin said so. Darwin is a god in evolution, so you can't criticize Darwin. If you do, you're branded as arrogant.

But any time a scientific theory is treated like dogma, you have to question it. The dogma of natural selection has existed a long time. Most people have not questioned it. Most textbooks still state this is so. Most students are educated with these books.

You have to question dogma. Use common sense. You have to think for yourself, without preconceptions. That is what's important in science.

[This article originally appeared in print as "We Are All Mutants."]

FROM THE MAY 2014 ISSUE

Digging Deep: How to Feed the World With Perennial Food Crops

A leading researcher dishes the dirt on potentially sustainable agriculture for a growing global population.

By Eliza Barclay | Monday, April 14, 2014

RELATED TAGS: AGRICULTURE, SUSTAINABILITY

Jerry Glover, a soil scientist, shows off a perennial wheatgrass plant's long roots, which grow deeper than annual plants' roots, improving soil structure and reducing erosion.

Jim Richardson/National Geographic Creative

More than 9 billion people will live on Earth by 2050. They'll need to eat somehow, but we're already running out of arable land. And many types of agriculture — including conventional farming of annual crops, which need to be replanted each year — leave fields nutrient-poor, reducing future productivity.

But soil scientist Jerry Glover is optimistic about feeding more people while conserving farmland soil. The solution, he believes, is to focus less on annual crops, which dominate world agriculture, and to embrace instead the potential of perennials, crops that can be harvested more than once without replanting.

Glover, a senior sustainable agricultural systems research adviser at the U.S. Agency for International Development (USAID), spent years as a researcher at the Land Institute in Kansas. There he realized the state's perennial grasses might hold the secret to protecting soil, reducing fertilizer use and getting multiple harvests out of one plant.

Farming, Glover discovered, could have a neutral, even positive, impact on the agricultural ecosystem. In 2008, *Nature* named 48-year-old Glover one of five "crop researchers who could change the world." *Discover* talked with Glover about his plan for doing just that.

Discover: Did growing up on a farm in drought- and dust-prone eastern Colorado shape your professional views?

Jerry Glover: I was certainly influenced by conditions there. I was seeing agriculture's tremendous damage to soil. But I also saw the potential and need for agriculture. I think we now have to look soberly at how our civilization has come about at the expense of the soil resource.

What do you think are the most damaging effects of conventional agriculture?

JG: Farmers harvest nutrients from the soil when they harvest their crops. And some of the nutrients are lost there on the farm through runoff — more than 50 percent of the nitrogen applied to wheat crops is lost before harvest. We need to close that loop. One of the biggest openings for that is to make sure that the nutrients that we put back onto the farm stay on the farm field and are used by the plants.

Most farmers grow annual crops, which have to be planted every year.

But in your research, you noticed that perennial grasses could be harvested repeatedly to make hay, with hardly any added fertilizer and without robbing the soil of essential nutrients like nitrogen and phosphorus.

Are perennial food crops the answer to feeding the world in the coming decades?

Glover pauses from his research on perennial trees to chat with Rhoda Mang'anya and her children on a her farm in the Dedza district of Malawi in Africa.

Jim Richardson

JG: I think they could be. Perennial crops can be grown for more than two years alone or alongside annuals, and they can radically improve soil health and support a healthier community of bacteria and fungi underground.

Annuals have to develop roots every year, which means their growing season is much shorter. Perennial roots go deep — some as deep as 10 feet — and they will sustain the plant for many years. Way down there, the roots can capture more groundwater. Those deep, better-established roots also help cycle nutrients in the soil and make them more available to plants.

And of course, the No. 1 [advantage of perennials] is preventing soil erosion. With better soil conditions, water will soak in instead of run off. Perennials also cover the soil for a longer period of time with plant material. So when the rain falls, the leaves and stems are there to intercept it and lessen the impact of rain. That decreases the chance the soil will be lost with the runoff.

Farmers around the world are starting to experiment with perennial food crops — both grains, like wheat and sorghum, and legumes, like peas and beans.

But what took so long? If perennials are so great, why haven't farmers bred them, up to now?

JG: The early plant breeders were farmers who were mostly focused on the first-year benefits of crops. And certainly t

Annual wheatgrass root growth (shown on the left side of each column) cannot compete with better-established, more robust roots of a perennial variety, which may be the future of farming.

The Land Institute

didn't have the awareness of some of the damaging impacts of agriculture that we do now because they weren't limited by land or resources. There wasn't the tremendous population pressure that we face now.

Now we also have much better tools in plant breeding. We have much more powerful, faster computers that allow us to sift through the genetic material to determine which characteristics are going to be more productive. And we have the urgent need of increasing food productivity. It's a perfect storm of opportunity and challenge, really.

Where should perennial crop research and development focus, at least in the near term?

JG: I recommend focusing first on the perennial types of legumes, given the protein needs of many of the developing countries. The great benefit is that legumes contribute to cropping systems; they can help take nitrogen out of the atmosphere and make it available in the soil. Also very promising and possibly in the near future would be perennial types of sorghum and rice. My agency, USAID, has awarded money to the University of Georgia to develop perennial sorghum.

You're now mainly focused on encouraging farmers throughout Africa to plant perennial crops that will feed people while maintaining soil health. Is soil there in worse shape than in North America?

JG: African soils were in general less fertile and less well-suited for agricultural production than American soils from the beginning. Farmers in Africa are often faced by the big challenge of working with inherently old, highly weathered soil. By this point, their soils have also been heavily eroded. And so that's where we need improvements most and most immediately.

Glover stands in a soil pit to compare exposed annual and perennial root growth at the Land Institute in Kansas in 2006.

Jim Richardson/National Geographic Creative

Where have you seen perennial crops be successful?

JG: I recently visited a system in Malawi [in southeastern Africa] in which pigeon peas, which can be grown as either an annual or perennial crop, are actually grown together with soybeans, which are annuals. Once the soybeans and pigeon peas are harvested, the pigeon peas are allowed to regrow. When they're regrowing, maize is planted into the pigeon peas. In the past, farmers would have grown just maize alone, or they might have rotated the maize with soybeans, but with this system they're now getting two harvests of legumes in one season — the pigeon peas and the soybeans — and then in the second season they're getting a harvest of maize and pigeon peas. So they're really increasing the amount of protein they're growing on their farm, and that's valuable both in terms of the nutrition in the household, as well as valuable on the market. From my point of view as more of a soil scientist, it really adds a lot of benefits to soil, too.

What are some of the obstacles to getting more African farmers to grow perennials?

JG: Pigeon peas are already quite widely used, but mostly as annual crops. Their perennial benefits could be much more widely taken advantage of. The obstacle to the other crops being adopted is that there just hasn't been enough plant breeding done to sufficiently improve perennial wheat and sorghum and test them in farmers' fields.

Do you think that perennial crops could be valuable and useful in the developed world, too?

JG: I think ultimately they could be more productive than our annual grain crops because they are able to capture more sunlight, water and nutrients. But the urgency in developed countries isn't there. The political will, the support by the farm community itself, probably isn't quite as great.

[This article originally appeared in print as "Feed the World."]

+

FROM THE JUNE 2014 ISSUE

Battling Infections By Silencing Bacterial Chatter

Princeton biologist Bonnie Bassler studies bacterial "quorum sensing" — the chemical communication that makes pathogens so dangerous.

By Cassandra Willyard | Wednesday, May 21, 2014

RELATED TAGS: INFECTIOUS DISEASES, MICROBES & VIRUSES

Zach Donnell Photography

Bacteria may be primitive, but they're far from simple. They lead complex lives and communicate through a chemical language that allows them to coordinate their actions, a process known as quorum sensing. Using this chemical communication system, bacteria can sense when they have reached a critical number, or quorum. Then they act en masse. Some might begin producing light, others a deadly toxin. This capability is part of what makes bacteria so terrifying: A single cell can't manufacture enough toxins to make us sick, but when millions simultaneously churn out noxious molecules, the results can be lethal.

No one has done more to decipher this bacterial lingo than Bonnie Bassler, a molecular biologist at Princeton University. In the 1990s, Bassler discovered that bacteria can converse not only with members of their own species, but also with other species, allowing them to sense their environment more comprehensively and decide when to launch an attack. Today her lab is hunting for compounds that can block this bacterial chatter to shut down infections such as cholera.

Bassler's influential work, along with that of other pioneering researchers, has transformed how people view bacteria. But much about quorum sensing remains to be discovered; scientists are still trying to uncover the molecules and mechanisms involved, and figure out how they operate outside the laboratory. And that's wha keeps Bassler captivated. “It’s a 4-billion-year-old mystery, and it’s going to take more than 20 years’ work from lots of labs to figure it all out.” *Discover* caught up with Bassler on a balmy summer day in her office at Princeton to talk about the history of her discoveries and what they might mean for the future of medicine.

Discover: What got you interested in bacteria?

Graduate student Yi Shao works in Bassler's lab. Half the team is figuring out quorum-sensing mechanisms; the other half aims to control the chatter.

Zach Donnell Photography

Bassler: I went to UC Davis because I wanted to be a vet. It’s a great profession if it’s right for you, but it’s memorizing the bones and the muscles, and I am terrible at stuff like that. Also, there’s a lot of blood and gore involved. We started to dissect these animals — god, ugh! I left the pig and walked outside and puked in the grass. I’m like, “OK, I hate this. I just hate this.” So I was basically lost.

Then my mother died of cancer in August of my junior year. I didn’t know if I wanted to be a doctor or a scientist, but I was going to do something about cancer. I went to see a biochemistry professor named Frederic Troy, who was working on a cancer project, and he agreed to let me work in his lab. But he put me on this bacterial project, and I’m like, “No way! I want to work on the important project.” But, of course, I had no skills. I couldn’t even pipette. So I thought, “Well, if I show him I’m really earnest and hardworking, then he’ll transfer me.”

I fell in love with these bacteria. I just love how sophisticated they are. They do everything that eukaryotic cells do: The way you metabolize glucose is the way a bacterium does. But they don’t have the slop of higher cells and higher organisms. They’re stripped-down versions. They’re a treasure trove of the most basic mysteries, and what we find in bacteria applies all the way up the food chain.

How did you get interested in bacterial communication?

B: I went to graduate school at Johns Hopkins. Saul Roseman was my Ph.D. adviser. He worked on how bacteria sense their environment, and he had gotten this little grant from the Office of Naval Research for studying how bacteria stick to surfaces, like boats or submarines. In the late ’80s, the Navy put on this symposium for everybody who had one of these grants, and I begged Roseman to let me go. I wanted to learn what other people in this area of marine microbiology were doing.

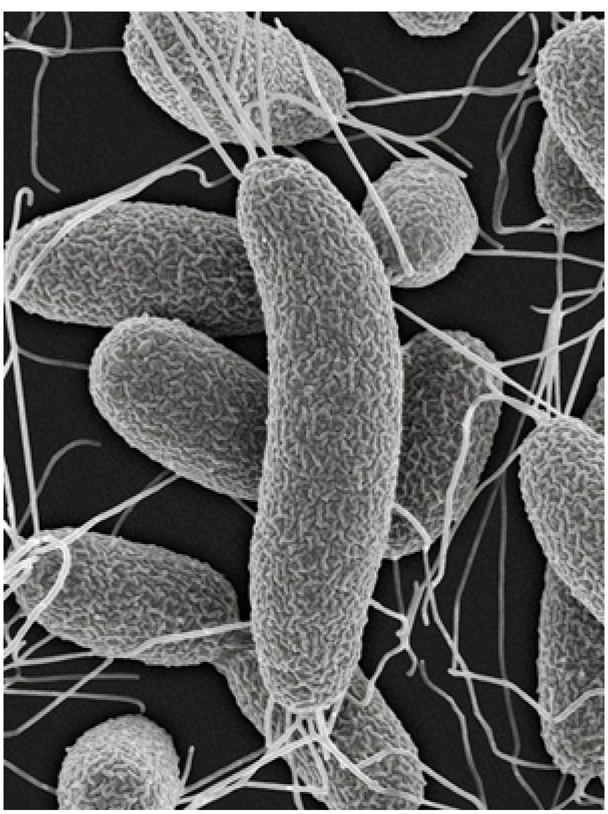
One of the speakers was Mike Silverman, a geneticist at the Agouron Institute in La Jolla, Calif. He talked about genetic work he was doing trying to figure out how bioluminescent, or “glow-in-the-dark,” bacteria turn on light when their cell counts reach a certain level. He was saying things like, “Don’t you see? This allows them to coordinate their behavior.” That went against everything anyone had ever learned. That idea that they were doing something as a collective was totally mind-blowing, at least to me. I literally ran up to the podium after his talk and begged him to let me be his postdoc.

Why was this so mind-blowing? Nobody understood that bacteria could work as a team back then?

B: Now we have hundreds and hundreds of examples of this. But at that time it had never occurred to me to think about bacteria acting in groups. Back then it was assumed by scientists, including most microbiologists, that bacteria were extraordinarily primitive, and that they didn't have the capacity to do fancy behaviors. They consume nutrients from their environment, they grow twice as big, they cut themselves in the middle and they make clones. So one becomes two becomes four. And it was always thought that when that happens, bacteria have no knowledge of their sister cells.

In the '70s, Woody Hastings at Harvard discovered that if you took a certain bioluminescent species of bacteria and you grew them, they made basically no light. And then when they hit a certain cell number, they would all turn on light together.

To figure out how this worked, he took bacterial cell populations of different sizes and spun each down in a centrifuge. Then he collected the liquid that the cells had been grown in to see whether there was some difference in the chemistry of the culture fluid. What he showed is if he took the fluids from cultures of cells that lit up and squirted them on cells that were at a low cell density, they all turned on light. You could trick the bacteria into thinking that they were at a high cell number. So it was clear there was something outside the cells, some molecule in the fluid. That was an amazing experiment. Hastings named the molecule an autoinducer: The bacteria "autoinduce" themselves to make this molecule and turn on light. But at the time many people considered that kind of coordinated behavior an anomaly of this sort of goofy glow-in-the-dark bacteria. Some people still doubted Hastings' conclusions, and even Silverman, when I met him, assumed the phenomenon was limited to just a few weird bacteria.



What had Silverman and Hastings learned by that point, and where did you come in?

B: Hastings and then Silverman worked on this bacterium called *Vibrio fischeri*, a bioluminescent marine bacterium that lives inside a squid. Hastings isolated the autoinducer, and then Silverman found some of the genes that control this system. They found that the autoinducer allows bacteria to count their neighbors. When a bacterium is alone, it dribbles out a couple of molecules and they just diffuse away. But if you have lots of bacteria together, the autoinducer will begin to build up. And when there's enough, it turns on a whole host of genes, including those involved in bioluminescence. The first investigators called this process "density sensing," and we now call it quorum sensing.

I worked on another bacterium, *Vibrio harveyi*. It's bioluminescent, too, but it is a free-living bacterium, so it encounters all kinds of different environments. We knew it made a similar autoinducing molecule, so we decided to t

It was in *Vibrio fischeri* that researchers learned that bacteria could count their neighbors.

Dennis Kunkel Microscopy

and unravel its quorum-sensing machinery. I just assumed that it would work the same as it does in *Vibrio fischeri*. I did the same experiment a billion times — looked for mutants that didn't make light, hoping I would have knocked out the quorum-sensing machinery. It should have been super simple. But the strategy of looking for dark mutants didn't help me find the right genes. I had this crisis of confidence. You think there's something wrong with you. And then, eventually, you say to yourself, "Perhaps I'm not thinking about this correctly."

It occurred to me that maybe the reason I couldn't get the correct genes is because there are two quorum-sensing molecules. It could be that when I knock out the genes for one, the other still works. That was an epiphany. If there were two molecules and you knocked one out, they'd still make some light. So I tweaked the experiment to look for mutants that were dim, not dark. My dim mutants were clearly lacking one molecule, but they still made something else. They were impaired, not broken. There had to be another molecule.

What was the second one doing?

B: I didn't have a clue. Why do you need two? I knew there was a second molecule out there. The genetics told us that molecule existed. But I didn't have that gene, and I didn't know the chemical structure of the second molecule. We took a lot of flack for that. The idea that bacteria could talk with *one* molecule was only starting to percolate through the community. So the idea that there were multiple molecules involved in bacterial coordination was so out there.

Your work showing that there had to be a second quorum-sensing molecule helped you get a job at Princeton, and in 1994 you started your own lab there. Did you figure out the purpose of the second molecule?

B: When I got here, we finally found the gene that made the enzyme that made the second molecule. But it wasn't just about finding the gene. We wanted to understand why *Vibrio harveyi* has this second molecule. So we sequenced the DNA of that gene. Our real hope was that our gene would look like some other known gene and give us a clue about what it did. There were about 40 genomes of bacteria sequenced at that time, and what you could do was compare your gene of interest to other genomes to see if they contained something similar. The computer would scan through all the known bacterial genomes and say, "Do any of them have that gene?"

That process took a long time back then. You type the DNA sequence of your gene into a database, and then you sit and you wait. I remember the screen filling up one by one. The database told us every bacterium that had been sequenced — not just the bioluminescent bacteria, but every bacterium — has it; they *all* make an identical molecule. And I said, "They're talking to each other. That's how they talk across species." That idea had not occurred to us. So that was an amazing moment. I still get goose pimples.

Did other scientists buy your explanation?

B: At first, the quorum scientists had trouble getting others to believe that bacteria could speak *within* their species. And then we came forward with this idea that they could talk *across* species — lots of people thought I was nutty. The dogma had been that bacteria can't communicate, so it was hard to accept that they could talk using two molecules, and even more difficult to imagine they could talk across species.

It takes a long time to change dogma. And there were still problems with the story. We had the gene, and the gene was in all these different bacteria, but we still did not have the identity of the molecule. So there was a chink in our armor.

In 2002, you finally identified the second molecule. And then you won the MacArthur "Genius" Fellowship, a grant awarded to individuals who show exceptional creativity. Did you feel vindicated?

B: That put me on the map. This prize is very coveted, and it also brands you as creative, not crazy. I'd been here at Princeton eight years, and I had never been able to adequately fund this lab. I was struggling to get money. I had been trying, trying, trying — writing five, six, seven grants a year. Most of my grants were getting rejected. And to get this thing that you didn't try for — that was so important for my confidence. And it branded quorum sensing as the hottest, coolest, most creative science.

You've now found that there are actually three molecules involved in quorum sensing. The first, the one Hastings found in the '70s, allows bacteria to count their siblings. The second allows them to detect other species. And the third, which is made by all bacteria in the *Vibrio* genus, allows bacteria to identify their "cousins," or extended family, giving them even more information. How do bacteria use these molecules to communicate?

B: What they first do is they scan the environment. And they're asking the simplest question: "Am I alone or am I in a group?" They just look for any quorum-sensing molecule. Then, the more sophisticated question that I think they ask is, "Who is that?"

They can say, "You are my absolute identical twin." They can say, "You're my extended family." And then they say, "You're some other species." They're not just counting. There's information encoded in these molecules that tells a bacterium who that neighbor is — how related they are. And depending on the ratio of those three molecules, they understand whether their family is winning or losing.

Why would they need to know that? How does that help them?

B: Having that information is extremely useful for decision-making. Bacteria aren't just swimming around. They live adhered to surfaces. Your skin, your scalp, your intestines — they're all covered in communities of bacteria, called biofilms. In order to make a biofilm, they have to secrete this substance that glues them all together, which acts like a shield. That's controlled by quorum sensing.

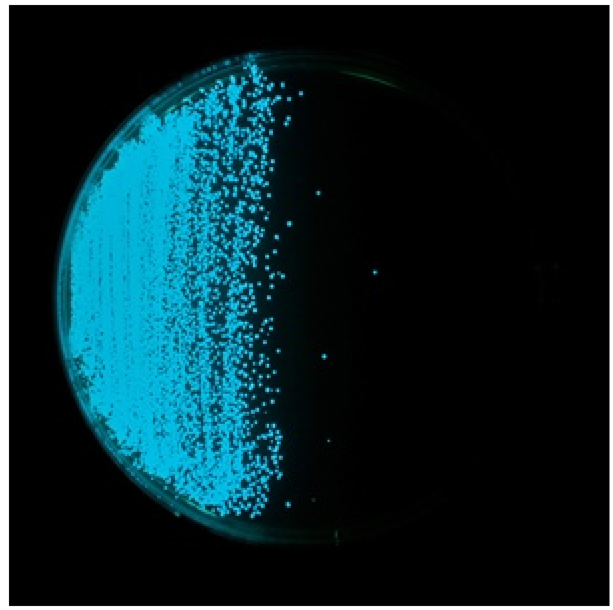
For these communities to be maximally productive, they can't be willy-nilly. They have to use multiple molecules to discern who their neighbor is — self or other — and to direct what job each participant in the community will take on.

Do you think the language of bacteria is more complex than we realize?

B: In 20 years, my field has gone from thinking of bacteria as asocial recluses to seeing them as at least being trilingual. And there's mounting evidence that this is going to be an inter-kingdom dialog. Humans and all higher organisms live in fantastic association with many species of bacteria. We speculate that the host makes molecules that tell the bacteria what to do, and the bacteria make molecules that the host is tuned into. It has got to be like that.

This field is only really 20 years old. And we just haven't found all the molecules yet. In the lab, we shake the bacteria around in a flask, and each bacterium perceives an identical environment. It could be that there's a whole set of molecules that they never deploy there. To find those, you have to put them in a much more realistic environment.

Quorum sensing controls bacteria's ability to cause deadly infections, allowing bacteria to secrete poisons, swarm and adhere to human tissue. Could you disrupt this communication to develop new ways to fight infections?



Colonies of the bioluminescent bacterium *Vibrio harveyi* glow in the dark in a petri dish.

Zach Donnell Photography

B: Pretty early on, quorum researchers started to think that maybe we could manipulate quorum sensing on purpose. The way molecules and receptors work, it's like keys fitting into locks. The molecules that are the real autoinducers turn quorum sensing on. But you could have another key that looks the same, but blocks the receptor. It binds, but doesn't send the signal. You can screen for or synthesize molecules that act as anti-quorum-sensing molecules. We've worked on three or four pathogens.

Have you discovered any promising candidates?

B: We can shut down quorum sensing in *Pseudomonas*, a notorious human pathogen, using a nematode, a worm model for infection. If you give our anti-quorum-sensing molecule to the worms, they live just fine. *Pseudomonas* also will kill human lung cells in tissue culture dishes. It's usually not very dangerous, except when it infects people whose lungs are already compromised — it can kill a person with cystic fibrosis. We've also found that in a petri dish, the anti-quorum-sensing molecule prevents *Pseudomonas* from killing human lung cells and from making a biofilm that would enable it to mount an attack.

In lab experiments it works. But by the time you're sick, quorum sensing has already happened. Can we really make a molecule that goes where you want it to go to stop an ongoing infection?

I don't know yet.

When you're doing this right, there are always more questions than answers. That's the fun and the torture of it. Bacteria had 4 billion years to evolve this capability. Scientists have been working on it for 20. This field is young. We are still pioneers.

[This article originally appeared in print as "Silent Treatment."]

FROM THE JULY/AUGUST 2014 ISSUE

Why We Can't Trust Our Memories

Brain researcher Elizabeth Phelps wants to understand why you think your memory's better than it actually is.

By Kat McGowan | Wednesday, July 23, 2014

RELATED TAGS: MEMORY & LEARNING

David Friedman

Early in her restless, inventive career, Elizabeth Phelps was trying to understand the deep structure of memory by showing word lists to people with amnesia — patients who'd survived a brain injury or stroke but lost the ability to remember. When she'd talk about her work with friends, somebody would eventually ask: What do word lists really have to do with memories — the vivid images and intense emotions that flood the mind? It's a good question. Why do you remember best the things that really matter to you? That question, among others, led her to explore emotion and the fascinating terrain where memories, fears and stress come together.

Ever since, Phelps — a past president of the Association for Psychological Science and a psychologist at New York University — has pursued questions that get to the heart of what it means to be human. She has investigated unconscious bias, decision-making and neuroeconomics, all while exploring how emotions influence the way we learn and remember: Why are memories for emotional events so vivid, and seemingly so hard to forget? What do we forget, and why?

To find the answers, Phelps uses the tools and principles of cognitive neuroscience, a discipline that explores how the brain gives rise to the mind: how neuroanatomy and the electrical activity of nerve cells relate to thoughts and actions.

Discover: Many people say we have a "rational brain" and an "emotional brain." Is there any truth to that?

Phelps: The idea has been there since the early philosophers. It's intuitive. But it's not scientific. It doesn't make any sense. It doesn't fit with what we know about the brain.

Elizabeth Phelps has long sought to understand how memories and emotions interact.

David Friedman

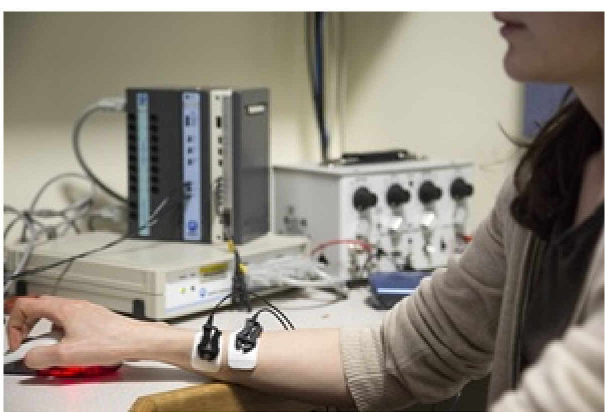
The way it's described — as if we have two separate tracts in the brain, one of which does emotion and one that does reason, with separate outputs — doesn't make any sense. It holds us back to think about these things so simplistically.

The role of emotion is to modulate your decisions, to prioritize. You *should* be influenced by things that evoke an emotional response in you. It would be unreasonable not to be. What emotion is telling you is, "This is something that matters to me."

I think we can be much more sophisticated and nuanced about how we understand the relationship between emotion and choices.

Philosophers have a lot to say about the human experiences you're interested in — emotions, memories, mental life. You were always interested in philosophy, and even minored in it. Why go the psychology route instead?

P: Studying philosophy, you'd spend forever talking about the structure of knowledge, the nature of human beings, or something like that. At the end of the semester, you'd be thinking, "OK, so what's the answer?" I started doing research on memory as an undergrad and liked it. To me, psychology was like philosophy with answers.



The memory studies in Phelps' NYU lab can include giving participants mild electric shocks.

David Friedman

What answers did you begin to find? What was your approach in studying the link between memories and emotions?

P: I went on two paths. One was to look at what emotion does with episodic memories — our ability to consciously recollect the events of our lives, what most people call "memory." The other path was to study fear learning — simple associations that are expressed physiologically through a bodily response such as a change in heart rate, skin conductance, arousal or pupil dilation. These are part of the fight-or-flight response, and they are easy to measure in the lab. In my lab, our first 10 years or so of research was on how we acquire fear. The second decade has been: How do we get rid of fears?

You and others have found that strong emotions enhance memory. But we often think our memory is more accurate than it really is.

P: The biggest misconception is that the strong feelings we have for highly emotional memories indicate they are more accurate. We've known this since cognitive psychologist Ulric Neisser studied memories of the explosion of the space shuttle *Challenger*. But it's so compelling. For example, people think they have totally accurate memories about 9/11. I wouldn't be able to convince you that you don't. But like any other memory, you actually forget most of the details.

You lived and worked in Manhattan on 9/11, and launched a study with others on how emotions influence memory. How did that happen?

P: Like everybody else, I felt I had to do something. An old friend and colleague, [neuroscientist] John Gabrieli, called just to see if I was OK, and the idea of doing a study came up. We had little booths on the street, and we surveyed people, asking some of the canonical questions in memory research: How did you become aware of it? Where were you, what were you doing, who else was there?

There was a lot of street traffic and the weather was beautiful, and people seemed to want to be around each other. We had a good response.

What did you learn when you followed up with the same people some years later?

P: In the study, people were about 50 percent consistent in remembering whom they talked to, but they were closer to 80 percent in where they were. It makes sense. Some details, because of their usefulness, are more important to remember than others. We're set up to capture time and place.

One of the more interesting things about emotion and memory is the fact that it gives us a heightened sense of confidence about the memory without increasing accuracy for a lot of the details: whom you were talking to, where you went afterward. I don't mean people forgot that 9/11 occurred. But people were wrong about all the little details about 50 percent of the time. You forget most of the details — but you don't think you forgot them.

So why does it feel like these intense experiences are perfectly preserved in memory?

P: The term for that is *flashbulb memory*. These are memories for highly emotional and traumatic events. The term is used because people have the feeling that these memories are so detailed and vivid that it's almost like a picture taken with a flashbulb.

In the lab, the way we measure this enhanced confidence is that I show you scenes that are emotional, such as car accident scenes, versus office scenes, which are not. Then I show them again later and ask you: Do you remember this scene with a lot of detail and context? Or does it just seem familiar to you? This is the subjective sense of remembering: Is it a strong memory or a weak one? Do I recollect all the little details?

We see a difference in brain regions for emotional versus neutral scenes. If it's a neutral scene, and you remember it in a lot of detail, we see more activation in an area called the posterior parahippocampus, which involved in remembering places or physical layout. [On the other hand] we see more amygdala involvement when you say, “Yeah, I really remember it in a lot of detail” if it’s an emotional scene. This suggests that you’re making the same memory judgment — whether the memory is strong or weak — but different brain systems are involved if it’s emotional as opposed to neutral.

What does this tell us? We know this posterior parahippocampus is important for memories for contextual details, such as location. We know the amygdala is important for enhancing your perception and attention for central threatening details. That makes sense: We should pay extra attention to threats in the environment. The cost is that sometimes we miss the other details. In eyewitness testimony, they call it “weapon focus.” At a crime scene, if someone has a gun, people are so focused on the weapon, they don’t remember the face of the criminal.

Maybe what’s happening is that for highly emotional situations, you’re getting really strong memory for a few details, but worse memory for a lot of other details. The fact that the memory for these few details is really strong leads you to believe you have strong memory for all the details.

So the upshot is that we can’t trust our own memories?

P: Memory does work. It’s good for a lot of things, but it’s not perfect. People have a naïve view of what memory is supposed to be like, that it should always be accurate. That’s not the case. Our memory works for us in our lives, which doesn’t necessarily mean it’s 100 percent accurate.

If there’s a threatening circumstance, you need the memory of it to avoid it in the future. Maybe something like whom you are with is not so important, but *where* it happened is really important. That’s what I think is going on.

What about you? How’s your own memory?

P: I don’t worry about it. When you do memory research, forgetting is a normal part of memory. Ever since I started studying amnesics, I realized I don’t have a problem with my memory because I met people who really did.

And I don’t believe people who tell me they do have a good memory. I don’t buy it. When someone says, “I absolutely remember you saying that,” I say — only in my head because it’s annoying — “There’s no way in hell you remember those details.” When people say, “Oh, I have a really good memory,” I think they actually have a bias about their memory. Usually they say that because they’re trying to prove that they’re right and you’re wrong!

After you studied how fears are acquired, you focused on how they’re forgotten. Will we ever be able to voluntarily forget our fears?

P: Initially, when you learn to fear something, you form an association — in our lab, for example, we often pair simple images, like a blue square, with a shock. Now you have a learned fear response to the blue square. This very simple notion is what Pavlov first described.

"Fear extinction" is when you learn that something that was in the fear domain is no longer aversive. In this example, the blue square is no longer paired with the shock, so you form a second association: The event (the blue square) that previously predicted the negative outcome (the shock) no longer does. To do this, you need activity in the [brain's] prefrontal cortex, which signals the cells in the amygdala to inhibit the expression of the fear memory.

This is the same idea as exposure therapy for phobias. Say you're deathly afraid of snakes. They'll first do something minor, like show you a picture of a snake, until you can deal with that. Then they'll show you a fake snake, or something like that, until your fear is diminished. You're repeatedly exposed to the thing, and you slowly diminish your fear response.

But the original fear doesn't go away. It's really a competition between the fear memory and the extinction memory. With the passage of time, the fear can come back, we think, because you never actually change the original fear memory. This may be why exposure therapy doesn't work all the time. A possibly more effective method is to try to change the original fear memory. That's why reconsolidation is so exciting.

How does reconsolidation work?

P: Every time you retrieve a memory, it's once again vulnerable. The idea with reconsolidation is that maybe we can target the actual fear memory — change it as opposed to inhibiting it.

So we could really get rid of phobias or fearful memories this way?

P: Part of the problem with talking about this is people who are truly suffering can get excited about it. It's not that we aren't excited about it. We are. But we're very far away from using this in treatment.

Ultimately, our goal is to be able to translate this and a lot of our other work to new methods of treatment that are more effective. We are nowhere close to that right now. That's why we do the research.

You also have researched how stress influences thinking. What have you found so far?

P: Stress has very uneven effects on brain systems. It impairs the prefrontal cortex, enhances the amygdala, and it might impair the hippocampus — all depending on the level of stress. So under stress, I'm going to get all these imbalances in decision and learning systems, and in social response systems. For example, we have one study showing that if you're under stress, you're more likely to attribute somebody's bad actions to who they are, as opposed to the circumstances.

What's underappreciated is how much the way we think about a situation influences our emotions. This is part of the inherent intertwining of emotion and cognition. Cognitive-emotional regulation is the idea that deliberately changing your thoughts about a situation can change your emotions. So you might have a predisposition to see the glass half-empty, but if you really decide to think about it differently, you can convince yourself that the glass is half-full. You're applying a cognitive strategy effortfully to change how you appraise a situation.

+

You make it sound easy, but for people who tend to see the glass as half-empty, it's very hard to start seeing it as half-full. Why is that so difficult?

P: We know from lots of work, not just mine, that the prefrontal cortex is required to effortfully change the way you interpret a situation, and the prefrontal cortex is highly sensitive to stress. When you're highly stressed, you're going to have problems with this form of regulation.

So how do we make these reappraisals depend less on the prefrontal cortex? For anything you learn that takes effort, the more you practice it, the more automatic it becomes and the less the prefrontal cortex is involved. It may be the case that when you're highly skilled at using a cognitive strategy to reinterpret, it becomes automatic.

For example, if you're afraid of parties, you have to go in there thinking about all the positive things that could happen, rather than the negative things. By reinterpreting what you think might happen, you might get better feedback from other people, and that might become how you naturally view parties. The more you practice it, the more it works. As it becomes more habitual, the less likely it is that stress would interfere with it — we haven't shown this yet, but it fits in with a lot of other science out there.

A lot of our work may be relevant to things like trauma and post-traumatic stress disorder because the neural circuitry of PTSD is built on the circuitry of fear learning and fear regulation. If we can identify ways that stress impairs us, we can think about strategies that might be more effective in situations where people are not adjusting so well.

Exposure therapy is the best treatment we have for phobias, but it doesn't work for everybody, and it may work less well in people who are highly stressed.

That's why reconsolidation is so exciting, because we have shown it diminishes involvement of the prefrontal cortex, which is impaired by stress. The hope is we can identify a faster, more effective, more long-lasting treatment. Clinically, we still have to prove that — but hopefully, we'll get there.

[This article originally appeared in print as "Hold That Thought."]

FROM THE OCTOBER 2014 ISSUE

How to Better Teach Kids Science? Just Ask Them

Neuroscientist Bob Knight started a kid-reviewed, kid-targeted online journal to inspire the next generation of researchers on their own terms.

By Gemma Tarlach | Thursday, August 28, 2014

RELATED TAGS: MEMORY & LEARNING

Bob Knight's kid-reviewed, kid-targeted online journal, *Frontiers for Young Minds*, now focuses on neuroscience but will expand to include medicine, astronomy and other areas of research.

Peter DaSilva

Kids say the darndest things when they're reviewing a neuroscience study up for publication.

That's what Bob Knight discovered when, almost on a whim, he started a kid-reviewed online journal — and found his passion.

Knight ran the Helen Wills Neuroscience Institute at the University of California, Berkeley, for a decade and was the founding editor of the online, open-access journal *Frontiers in Human Neuroscience*. His pages-long list of published studies is the envy of any academic, but Knight still has the straight-talking style and self-deprecating wit of a kid who grew up on the blue-collar Jersey shore.

It's Knight's combination of endless intellectual curiosity and down-to-earth realism that led him to start *Frontiers for Young Minds* in 2013. He wanted to inspire the next generation of researchers, but on their own terms.

Like the rest of the *Frontiers* series, the journal is online and open access, but *Frontiers for Young Minds* is reviewed for, and aimed toward, children. Although initially evaluated by an adult member of the editorial staff, each study posted at the site must also make it past a "kid reviewer" age 8 to 15.

Originally recruiting the reviewers from English-speaking children of neuroscientists around the world, *Frontiers* is now focused on expanding. A seventh-grade inner-city class recently reviewed a study on the neuroscience of dance, for example, and Knight's staff will roll out Spanish translations of articles in 2015. There's even a Chinese version in the works. The journal is also broadening its coverage beyond the study of the brain.

Knight took some time recently to talk to *Discover* about brains, baloney and pop star Beyonce — and how *Frontiers* fits into it all.

Discover: What drew you to neuroscience in the first place?

Knight: I came to neuroscience through clinical neurology, which studies diseases of the nervous system. I like areas dealing with connectivity, and I liked the detective story aspect of it: to go into a room, take a patient's history and have a good idea of what was going on.

At the Helen Wills Neuroscience Institute at UC Berkeley, Knight demonstrates an electroencephalogram and eye-tracking equipment to students from Berkeley's Summer Institute for the Gifted.

Peter DaSilva

Where did the idea for a kid-reviewed, kid-targeted journal come from?

K: Six years ago I was in a meeting about the future direction of the review process for a journal. I half-jokingly said, "Why don't we have kids review it?" The idea stuck in my head.

So how does the whole process work? The researcher submits a paper through kids.frontiersin.org, and it's assigned to a kid reviewer?

K: There's a pre-step there: We look at it first. We don't want to control structure, but we want to make sure there's a clear hypothesis. We want the same thing for the kid reviewers. We want them to understand the scientific method, and to ask whether the author had a hypothesis and conducted an experiment that allowed them to test the hypothesis with a yes or no answer to a question. The review comes in [from the kid] and that's it. There's no back and forth.

How tough are the kid reviewers?

K: The kid reviewers are brutal! A 14-year-old boy reviewed a paper on the relationship between the brain's reward system and Facebook likes and concluded: "The research is interesting, but it's not obvious how this knowledge will help with anything." The researcher went back and changed the paper to make its value clearer. In the usual journal review process, a couple of people review the paper and send it back with comments, and the author grumbles and then enters a discussion: "OK, I'll change this but not that." But in our process, whatever the kid says to do, the author has to do, or it doesn't get published.

Researchers today are arguably more time-crunched than ever. Why should they bother getting involved with a journal aimed at children rather than their peers?

K: It's their duty. They need to be involved in education. They need to be teaching the next generation of researchers, or we'll go backward and in 30 years, we'll all be pushing handcarts again.

And for young scientists, those early in their careers, there is an immediate payoff. When you come up for tenure, you have to show your work in three areas: research, teaching and public service. This hits all three.

And what's been researchers' response to *Frontiers*?

K: Look, if I started a new journal and sent out a request for associate editors, maybe 10 percent of the people I contacted would say yes. With this, I contacted 52 people and 47 said yes. They're interested.

How big of a staff does *Frontiers* have?

K: I'm the chief editor, Fred Fenter is the managing editor and Noah Gray calls himself the "engagement editor" — he's our social media guy. We have 15 areas [within neuroscience], and each area has three associate editors. The number of kid reviewers is growing all the time. It's important to me that we recruit reviewers from the whole spectrum of society, so we're starting outreach programs, and our Berkeley students have really stepped up to participate and be mentors.

Is *Frontiers* publishing original research, or has it appeared elsewhere already?

K: The papers have appeared elsewhere. There are two kinds of papers we review: a paper you just published and now want to do a kid-friendly version of, or a review article that draws on previous research. We're working on a system where, when a researcher gets an acceptance email for a peer-reviewed journal, they also get a note saying we'd like you to consider submitting a kid-friendly version.

Scientists have a duty to inspire the next generation of researchers, says Knight, shown here explaining the workings of an MRI with the help of a young volunteer.

Peter DaSilva

All of this sounds time-intensive and fairly expensive. You recently secured $480,000 in funding over the next two years from the Jacobs Foundation and are pursuing additional philanthropic grants, but have you considered charging for the site or finding a corporate sponsor?

K: I want to make sure nobody ever commercializes this. I want it to be open source. I want it to be free for everyone. A lot of people involved in online projects will say it's all kumbaya, we'll do it because we love the world. Baloney. They'll do it because they want to make zillions of dollars. We're not going to slap ads up on the site. But our budget to do this is about $1.2 million a year. That's a lot of dough. To keep it open access, I've got to line up that money. I'd like to stick to government agencies and foundations, but if some big corporation offers me $500,000, I'm not going to turn it down. But I'm not going to put ads for them on the site, either.

OK, so we're not talking from a marketing perspective but, from an audience perspective, among children, who is *Frontiers'* prime demographic?

K: You know, I was just at the D.C. science festival. It was incredible. There were 35,000 attendees, and I think 10 to 12 was the average age. That's the right age. It's becoming clear to me that this is not a high school science club journal. *Frontiers* is a middle school journal to get kids engaged in science, to show them how fun it can be. It's about analytical thinking and understanding the scientific method, which will help them figure things out in their lives, not just in science. It's about using more analytical thinking, not just emotion-based.

Do you think it's a basic lack of analytical thinking that is causing Americans to fall further behind other countries in science literacy, or is it how we're teaching children? Or is it perhaps how issues such as climate change and evolution have been politicized?

K: I think first you have to make clear that there's a difference between ignorance and intelligence. I was raised in Laurence Harbor, N.J., and I think I was only the second person from there to go to college, though the kids there were just as smart and creative as the ones I come across here [in Berkeley]. The reason I'm doing [*Frontiers*] is because education was the ticket for me — it's the only thing that makes up for a lack of socioeconomic access.

Telling kids you have to believe in climate change, or you have to believe in evolution, is not going to go anywhere. You have to let them figure it out, to explore the world, to test their ideas. That's the only way you're going to get change. Trying to change things from the top down never works.

So, would you include *Frontiers* as part of the Science, Technology, Engineering and Math (STEM) trend in education?

K: This STEM thing that everyone's always talking about and touting is all top-down. People are telling kids do this, do that. I've never heard anybody say, "Maybe the kids should tell us how they want to be educated."*Frontiers* is about putting kids in control. We're not there yet, but in the future I'd eventually like kids to be the ones guiding the material and driving the content.

Aside from STEM, another big trend now in science education is citizen science: projects, often crowdsourced, in which non-scientists, including children, contribute to research through collecting data or analyzing it. Do you see *Frontiers* evolving a citizen science component?

K: I don't know. I'm about to set up a parallel editorial board of kids. If they tell me, "Hey, we want to crowdsource something," fine, but it's got to come from them. I don't want to tell them what to do.

A common criticism of the gulf between researchers and the public in science understanding and interest is that many researchers aren't able to explain their work in terms the average American can understand or find relevance in. Do you think that's a fair critique?

K: I think most scientists can talk about what they're doing and why it's important if you let them. But I think most journalists don't give them that chance. They think scientists are these weird, geeky people. And kids have the role models that the press promotes. I heard that the No. 1 role model in the world is Beyonce — give me a break. If that's true, we're in the most shallow end of the pool.

Where will *Frontiers* go from here?

K: When I first came up with the idea, we were going to call it *Frontiers in Neuroscience for Young Minds*. But we took out the neuroscience part. That was a calculated decision. We will be expanding: The next three areas we're exploring are medicine, which is huge — everything from asthma to pimples to obesity; and astronomy, which is a natural — kids wonder what's up in the skies; and environmental science. We're definitely going to branch out. But we want to grow it organically. We want to be a portal for good information for kids. You have to go through us and you have to go through our scientists, but once it's vetted, we post it.

So, is *Frontiers* going to be the answer to motivating kids to want to emulate scientists rather than pop stars?

K: Is it just a cool website, or is it going to change things long term? I don't know the answer to that. We have to wait and see. Things aren't going to change in five or six years. It's going to be a generation. But I would like to think *Frontiers* is a small building block leading to that change.

[This article originally appeared in print as "The Kids Are All Right."]

FROM THE OCTOBER 2015 ISSUE

The Man Who Coined 'Biological Diversity' Tries to Save It

Thomas Lovejoy argues that it's not too late to restore threatened ecosystems.

By Richard Schiffman | Thursday, August 27, 2015

RELATED TAGS: EARTH SCIENCE, NATURAL RESOURCES

Thomas Lovejoy has spent decades studying ecology and biodiversity, including several years examining the fragmentation of the rainforest in Manaus in the Brazilian Amazon, where he recently returned (above).

Slobodan Randjelovic

For the past half-century, Thomas Lovejoy has studied “the shimmering variety of life on Earth” in the Amazon rainforest. The 74-year-old tropical biologist, who teaches at George Mason University, coined the term biological diversity in 1980 to refer to the millions of different species that comprise life on Earth, of which scientists have documented perhaps 10 percent. Unfortunately, countless organisms will vanish before we ever discover them, let alone investigate their potential benefits in fields like medicine, agriculture and genetics. But if we work now to restore ecosystems, Lovejoy argues, we can avoid the worst of these losses — and slow down climate change, too.

Discover: Scientists say we face the largest mass extinction since the disappearance of the dinosaurs. You have pointed out that it isn’t just species that are going extinct — it’s entire ecosystems. Which ones are most threatened?

Thomas Lovejoy: Most of the lowland tropical rainforests in Southeast Asia are already gone. Africa is now up for massive deforestation. We’re seeing huge die-offs in the coniferous forests in western North America, to the parasitic pine bark beetle. Native grasslands everywhere are being replaced by farms and pastures. The list goes on.

D: What's causing these declines?

L: Habitat destruction is probably the leading cause. Wild places are vanishing fast. A close second is the spread of invasive species. There is also pollution — the soup of toxic chemicals we live in, the fact that we have distorted the nitrogen cycle with our wasteful overuse of synthetic fertilizers. And coming up fast on the outside is climate change.

D: As the climate shifts, can't species just migrate to more favorable areas?

L: It's already happening. Joshua trees are moving northward out of Joshua Tree National Park. Fish in the oceans are migrating to cooler waters. But species can move northward only so far. At a certain point, ecosystems simply disassemble, and the surviving species will reassemble into something hard to imagine.

D: You've called for "re-greening" the planet — namely, restoring ecosystems — to put the brake on climate change. How would that work?

L: A significant portion of the excess CO_2 in the atmosphere is from centuries of destruction and degradation of ecosystems. A concerted effort to do ecosystem restoration around the world could pull about half a degree of warming out of the system before it actually happens. For example, tropical forests can be brought back on marginal agricultural land. Native species can be reintroduced to places where they've vanished.

D: How do you envision funding ecological restoration on a meaningful scale?

L: There simply has to be an appropriate price for carbon that reflects its actual cost in terms of the climate disruption that it creates. And if we all pay a bit more for fossil fuels — which means we are less wasteful of them — some of the revenue from that could go into these projects. I don't think it takes a lot.

[This article originally appeared in print as "Biohazard Warning."]

FROM THE APRIL 2017 ISSUE

Q&A: Yuri Milner

Russian-born entrepreneur co-founded the Breakthrough science prize.

By Steve Nadis | Friday, March 10, 2017

RELATED TAGS: PHYSICS, SPACE EXPLORATION

Andreas Rentz/Getty Images for Hubert Burda Media

Yuri Milner was pretty much destined to do something in science. Born in Moscow in November 1961, he was named after Soviet cosmonaut Yuri Gagarin, who, about six months earlier, had become the first person to venture into outer space. Inspired by Carl Sagan and others, Milner majored in physics at Moscow State University. Then, in the middle of earning a Ph.D. in particle physics, he quit. Eventually, he started his own internet company and invested in other companies like Facebook, quickly amassing a fortune.

Since then, Milner has used his wealth to support science. He co-founded the Breakthrough Prize, which recognizes important advancements in physics, life sciences and math by awarding $3 million prizes in each category.

Milner spoke by phone with *Discover* contributing editor Steve Nadis days before the fifth annual Breakthrough Prize ceremony in December in Silicon Valley, where Milner now lives.

Q: Did you abandon a research career in physics because you felt you could do more to help science from the outside?

A: I quit physics around 1990 when I decided I was not good enough to make a big contribution to the field. But I continued to track developments in science. It's like your first love — you want to keep in close touch.

Q: What prompted you and your friends, including Facebook CEO Mark Zuckerberg and Google co-founder Sergey Brin, to start giving out prizes, first in physics, then in other branches of science?

A: Recognition of science among the general public is lower than it should be, partly because it is not easy to explain. We need to explain science better, communicate it to a wider audience and celebrate it. Because, in the end, science is really the biggest asset our civilization has.

Q: In addition to regular Breakthrough Prizes, you're awarding Special Breakthrough Prizes for big discoveries like gravitational wave detection, plus awards for young researchers and middle and high school students. Are there plans to further expand the scope of these prizes?

A: Not in terms of subject area. The prizes focus on natural sciences — physics, life sciences and math — and we don't plan to go beyond that. But that still leaves a lot of ground to cover.

Q: *Discover* has covered Breakthrough Starshot, a plan to develop light spacecraft capable of reaching the nearest star, Alpha Centauri, about 20 years after being launched. You've pledged $100 million to this project. Can you tell us about your other initiatives?

A: We started something called Breakthrough Listen in 2015. The first search for signs of intelligent life beyond Earth was undertaken by Frank Drake in 1960 at an observatory in Green Bank, West Virginia.

Breakthrough Listen's search for radio signals of extraterrestrial origin is using a new telescope at Green Bank that's vastly bigger and more sensitive. Joining this effort are new telescopes in Australia and China, so we now have three of the four biggest radio telescopes in the world. Combined with the most sophisticated computer hardware and software available, we'll see if we can make some progress. These new searches should be much faster and more efficient than what we could do just a year or so ago.

Q: What's the status of the latest initiative, Breakthrough Message, which will offer a $1 million prize?

A: We haven't launched this one yet, but the general idea is for a competition, open to everyone, to craft a short message that would best represent humanity to another civilization. What is it that really defines us as a civilization — not just in this country [the United States], but all of us?

+

FROM THE MARCH 2018 ISSUE

A Professor's DIY Spacesuit

Cameron Smith will put his suit — and his life — on the line at 50,000 feet.

By Katherine Kornei | Thursday, April 26, 2018

RELATED TAGS: MATERIALS SCIENCE, SPACE EXPLORATION

Travis Stanton

+

Anthropologist Cameron Smith usually digs into the past, but these days, he does a lot of forward thinking. The Portland State University professor spends his spare time and money designing and building a spacesuit. He wants to make one with a price that's about 1 percent of a comparable NASA getup, which costs roughly $70,000.

This year, he'll put his life on the line to test his design by piloting a hot air balloon by himself to about 50,000 feet, far above the altitude of commercial jetliners.

Smith's designs have attracted the attention of SpaceX, but the 51-year-old isn't interested in profits. He's committed to making his spacesuit plans freely available online. *Discover* joined Smith at his downtown Portland condo-and-workshop to learn more about what drives this explorer.

Q: What's an anthropologist doing designing a spacesuit?

A: I grew up in Texas when the culture of the Apollo missions was still reverberating. But in those days, the path to space was military flying, and my eyesight wasn't perfect. So I turned to archaeology and anthropology, which took me to really wild, remote places. I built sails for ships as part of my research and became comfortable working with textiles. And in the last decade, the proliferation of the private space industry prompted me to think about participating in some way. Many space exploration technologies can benefit from reinvention and rethinking — a lot of this hardware hasn't been re-evaluated since the 1960s.

Q: Tell us about your upcoming balloon flights.

A: Some of my trained volunteers and I have done a handful of test flights, and we're now pulling together the resources — money, an RV, a pickup truck — to stay in the field for weeks at a time in a "mobile flying camp." We'll be pushing into the 20,000- to 30,000-foot range this year. There may be things going on with a spacesuit that you don't notice until someone is looking at it from the outside. But I'll have to go up to the really high altitudes alone because my balloon's volume provides enough buoyancy to lift only me and a lightweight life-support system through that thin air. I'm going to be very cautious. You've got only about five to 15 seconds of useful consciousness up there without a spacesuit. I don't want to get injured or killed.

Q: Why not just test the spacesuit in a pressure chamber?

A: Space-equivalent conditions, like those at 50,000 feet, include a major problem that's hard to replicate in pressure chambers: very low temperatures. Imagine what metals and adhesives do at minus 100 degrees Fahrenheit. I want to have my invention keep me alive in those conditions.

Q: How many other people do you know of who are taking this DIY approach to spacewear?

A: Every couple of months, I get an email from someone who wants to design a spacesuit. I'm happy to share a lot of what I know, but after a while, most people start to realize it's a lot of work. I don't know of anyone else designing a spacesuit privately.

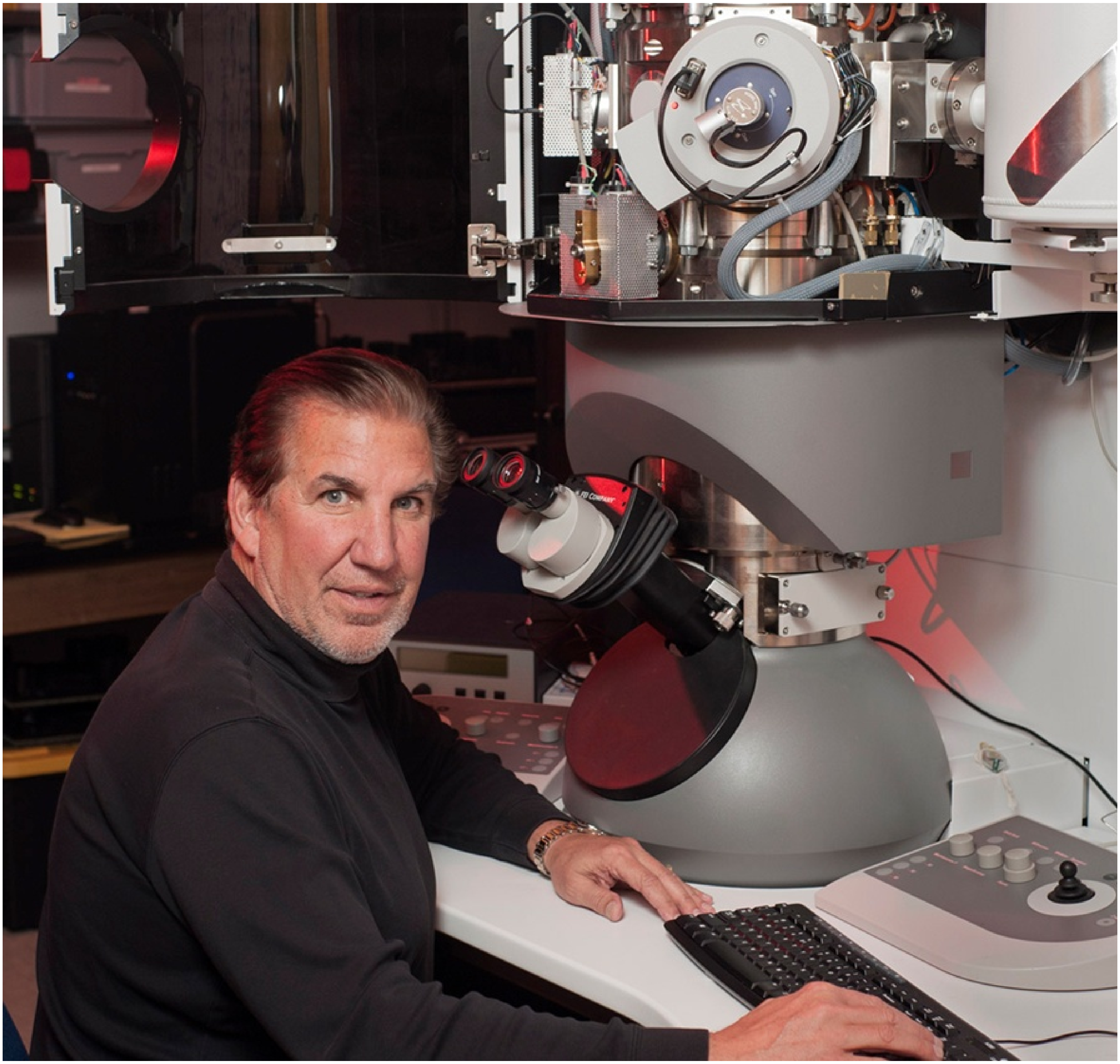
+

FROM THE NOVEMBER 2018 ISSUE

Meet the Man Who Takes Pictures of Microbes

Zoom in on four decades of microscopy advances.

By Ernie Mastroianni | Thursday, October 18, 2018

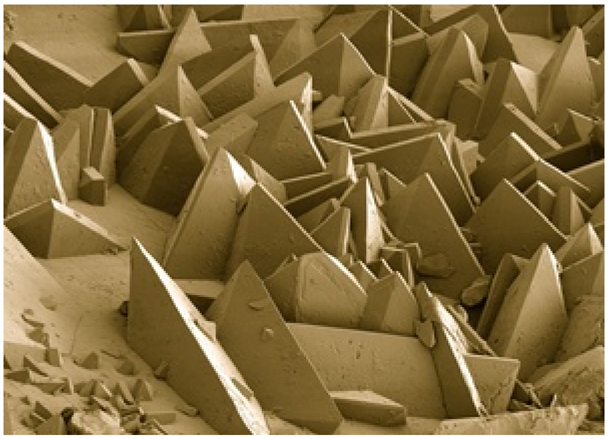


Ernie Mastroianni

High school senior Thomas Deerinck didn't expect his life to change when he walked into his science class one day in the mid-1970s. Local research scientist Betty Barbour had come to share her stunning images of the microscopic world. She was hoping to recruit students for her electron microscopy training program, eager for new helping hands. Deerinck promptly enrolled.

Forty years later, his award-winning photos have appeared on the covers of scientific journals. He's also one of the most senior researchers at the National Center for Microscopy and Imaging Research in La Jolla, California, where he and his colleagues expand the boundaries of what a microscope can see and do.

But as his subjects have gotten smaller over the years, the large streams of data the photos produce need heavy-duty processing.



The jagged surface of a kidney stone.

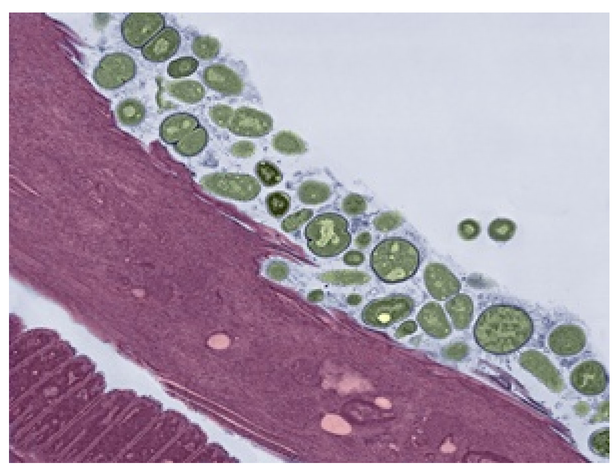
Thomas Deerinck/NCMIR

Recent images of slices of a mouse brain require a supercomputer to assemble them into a 3D model of individual neurons and synapses. The image files are big, and the 3D models are even larger, so managing data is key. Deerinck has learned that when the microscopes can see individual atoms, his small world becomes almost impossibly huge.

Q: When you started in 1978, what was the state of microscopy?
A: Techniques and instruments were similar to those used for decades. We shot everything on film since there were few computers and no digital cameras.

Q: What have been the some of the breakthroughs in the last four decades?
A: In the mid-'80s, a special tool called a laser scanning confocal microscope revolutionized light microscopy by allowing us to image thick biological samples without out-of-focus blur. In the '90s came green fluorescent protein, which makes different parts of living cells visible. We could do time-lapse imaging and see cell components interacting over time and in three dimensions. The next advance was electron tomography, where we use a high-energy beam of electrons to image a specimen from different vantage points to produce a 3D representation. It's like a CT scan, but with thousands of times better resolution.

Q: What sort of microscopy challenges are you working on now?
A: To improve our ability to image the mesoscale — the middle scale between macro and micro — where you can photograph the structure of an organ, such as the brain, all the way down to the individual protein molecules. Currently, there's no way to continuously image that entire range.



A human tongue (purple) with surface bacteria (green).

Thomas Deerinck/NCMIR

Q: So how will you get there?
A: It's going to be a combination of robotics, deep-learning computer algorithms and just improvements in the actual microscopes. We try to bring all these things together: how you prepare your specimen, choosing the right platform to image it, optimizing the platform itself and then how you deal with the deluge of data.

Q: How do you make such technical photos that are also aesthetically appealing?

A: I have been married to an artist for 30 years, and she is always looking at my images and saying that I should come at it from a nature photography perspective. There should be an up and there should be a down, paying attention to color, contrast and composition. Many people don't realize that the amazing beauty of nature extends to the microscopic world.