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Freeman Dyson's Brain

By Stewart Brand

Stewart Brand talks to the deepest futurist alive - and the most trustworthy.

Freeman Dyson is renowned in science circles not only for his rigor and insight, but for his science fiction imaginativeness and populist ethics. Though raised and educated in England, Dyson, a retired professor of physics, has spent the last 45 years at the Institute for Advanced Study in Princeton, New Jersey. He's best known for his work in quantum electrodynamics, but his professional reach extends far beyond the academic community. Dyson's popular books, such as *Disturbing the Universe*, *Infinite in All Directions*, and, most recently, *Imagined Worlds*, are esteemed among scientists, technologists, and the public alike. In person he is soft-spoken and unassuming, and at 74 he's neither frail nor hesitant. During our three-plus hours together, we talked about his childhood and his daughter Esther, about some of the greatest scientific breakthroughs in history, about why he thinks that PhDs and theology should be abolished - and we covered an array of cosmic ecology ideas he has for a better future.

The substance of what he said changed my mind on nearly every subject he addressed.

Brand: I was looking at your 1988 book, *Infinite in All Directions*, and remembering what it was that excited me about it. Ten years ago, most people I knew were in the depths of a kind of bad mood, harboring a pessimistic feeling that things were going to keep getting worse for the rest of their lives. But your book had this pragmatic and also rather cosmic optimism about it; it came as a complete counter to the cultural flow at that point. Did you perceive that at the time?

Dyson: Oh yes. It's partly a matter of what generation you came out of. I grew up in the '30s, which was a really black time. Having survived that, you can never really take pessimism seriously. World War I was *the* great tragic experience for England, so we grew up under its shadow. A tragic view of life was everywhere; there was nothing *but* tragic.

How were *you* feeling then?

I was a complete fatalist. I didn't expect to survive. When we saw World War II coming along, we thought it would be bacteriological, and we all expected to die of the plague. So in the meantime we had a good time. The war was so much more comfortable and manageable than we had ever imagined it could be.

What's your sense of cultural optimism right now?

Things are going amazingly well. Of course, there's all sorts of monstrous injustices in the world, but I look at my six kids and they're all doing fine; all of them have interesting lives. Younger people have so many opportunities. I don't see any pessimism among them.

I wonder how this relates to pace, because you, more than anybody, like to think in the long term - in centuries. Whereas a lot of our behavior seems to respond to what we think at the year level or the next-week level. Is there more optimism in the longer view because you can better even out the ups and downs of daily life?

Yes, by and large.

Maybe there is a science fiction angle I can use to describe this sentiment. Science fiction has gone through periods of *up* excitement: "Let's explore the universe; this is going to be fun." Followed by: "It's pretty dire out there; we're going to have a nuclear war." To, more recently: "It's going to be a tough, corporate, dog-eat-dog world, and all we can do is try to find our way in that." What's your sense of the flow of science fiction moods?

I haven't been following recent science fiction. The people I tend to read are my old friends, who are definitely not on the cutting edge. There's Bob Forward, who is old-style - what they call hard science fiction. It's good, but it's not very imaginative. Then there's Charles Sheffield and Paul Preuss, whom I like. I don't even know who the young people are.

Have you read Vernor Vinge?

No.

He has a proposal he calls the "technological singularity." It comes up in a couple of his novels, now collected in a book called *Across Realtime*. The supposition is that early 21st-century technology (with culture trying to stay apace) has accelerated so rapidly that everything is fundamentally changed. You can see this acceleration now with Moore's Law, or with the Web taking off because its value increases by the square of the number of people using it. These are basically self-enhancing technologies. You also have tremendous acceleration culturally and commercially as people are rewarded for being quick on the uptake and punished for being slow. All of these accelerations together create an event horizon over which you can't see the future anymore because of the pace of change. That's what makes it a singularity. Vinge says that we're rapidly approaching the point where the computer's ability to handle information equals the human brain's in terms of complexity, speed, and so forth. Does any of that resonate with you?

Not at all. The technical tricks these people are talking about are only a small part of the human experience. They vastly overestimate their own importance. I look at the world in a very different way. It's partly a matter of being old, but I look at the subway networks in cities, for instance. They also have the N-squared law. If you have a subway network with N routes, its value to the passenger is N squared. That's fine. But once you get to a certain number of routes, like 20 or so, there's very rapid growth, followed by saturation. This will also happen with chips. To some extent, it already has. It's true that the price per megaflop is going down according to Moore's Law, but what you can do with the processing power isn't increasing at the same rate.

I remember doing a study on the cost of nuclear power in the 1950s, when people thought it would be very cheap. We studied what the economic effect would be if the cost of electricity were zero. The answer is, "Not much." It costs far more to use electricity than it does to make it. There's about a 5 percent drop in the GNP if electricity is free. So cheap energy is all it takes. The same is true of computing power.

Is this a self-limiting revolution, then?

Yes. It won't completely choke itself off, but other things are much more important.

The top of the list being ...?

I've been propagating a view about a return to village culture that may be the subject of my next book. The really bad things going on now are mostly connected with megacities that are growing out of control - places like Cairo and Mexico City.

I wonder what the impact of the Teledesic project will be on these megacities. It appears that we'll get anticipatory effects in this decade and much stronger results in the next decade. We'll equalize every place on the planet in terms of cheap data access. It's an extraordinary technical jump for everyone all at once. Part of what cities offer is their information infrastructure. But with Teledesic, you get city-quality information infrastructure in the countryside. It becomes anybody's countryside - Mexico's, Egypt's, China's, any country in Africa. Is this the sort of shift you're talking about?

That's exactly what I had in mind. There are three items I cover in the new book. First, I didn't know Teledesic was going up, but I knew something like it was always within 10 years anyway. The second is solar energy, which is wonderfully world distributed. It's only a question of a factor of two to five between the cost of solar energy and the cost of oil. In the long run, oil will get more expensive and solar energy will take over. The third item is biotech, which is essential for using solar energy in crop plants designed to do all the industrial processes.

So you're not talking about solar electricity.

That's also part of the deal, but the more important thing is that you'll be able to make your gasoline locally. People will live in the villages and commute to work in the towns, and they'll produce gasoline on the local farms.

This is from biomass that you refine right there?

You don't even have to refine it. The plants produce it.

Isn't this a more complicated process?

True, we don't have the biotech yet. For that I'm talking maybe 50 years - when we really understand how DNA functions. However, there's no reason plants should be limited to 1 percent energy efficiency. We know photovoltaics can reach 10 percent quite easily. Plants are stuck at 1 percent because they use a particularly elegant process involving chlorophyll. But it's wasteful; it involves a long chain of chemical reactions. It's a historical relic that plants got stuck with. If you could design a plant from scratch, you'd probably use silicon films instead of chlorophyll to collect sunlight. Silicon is abundant, and you've simply got to have a plant that will process soil and extract silicon the same way that plants now process carbon dioxide into carbon.

Presumably, plant-food efficiency also goes up enormously with biotech. So you can get food anywhere and energy anywhere. And with Teledesic you can get bits anywhere.

That's the point. The example I like to talk about is the village in East Germany where my wife grew up. It's typical of what happens to villages. Under the communists, it was a very stable and prosperous farming village where they used 1910 technology. They sold their stuff to Russia at a fixed price, so everybody was guaranteed an income. The system offered complete security and a very comfortable, well-organized way of living.

The village also had a little zoo. A local communist decided it would be a good idea, and the party agreed. The zoo didn't even have to be profitable. There were a couple of professionals to take care of it, and most of the work was done by schoolchildren, which was marvelous for them. It was a very fine example of communism as it should work. Then came 1990. The village economy was swept away in one year after Germany was unified. You had to pay in West German marks to buy goods. The Russians couldn't afford to buy anything. Suddenly, the local people preferred to shop in the supermarket - stuff imported from France and Denmark. The global economy just wiped the place out. Most of the village was out of work, and the younger people simply moved to the cities in hopes of finding jobs, leaving behind those with pensions.

So your sense of how we might return to the villages ...

I haven't got there yet. This is a three-act play. Act II is the collapse, produced by the market economy. Of course, it's happened all over the world: villages destroyed by the global economy. They can't produce anything anybody wants to buy, so the people just move out. That's what produces this tremendous migration into the big cities, which doesn't solve anything. Act III is what's happening now. The village is reviving.

Your wife's village?

Yes. It's gentrifying. This is the way it has to go. Wealth is moving into the village. They are new people with money and Mercedes cars, and they have a love and respect for the beauties of nature.

Do they have any respect for the people who stayed there during Act II?

Oh, yes. It's a place that is starting to be friendly again, and there's a 1,000-year-old church in great need of repair. These new people are taking care of that, and they're widening the roads so their Mercedes can get in and out. It's a place for people to live who bring in the wealth from somewhere else. That's the way half of the villages in England are, too. They're beautiful, but the farming is mostly amateur farming.

Well, now, you're a futurist. This is Act III in a play with presumably more than three acts.

The point I'm building up to is that you can't do this in Mexico, because there isn't any wealth. The villages are too isolated; it's a much bigger problem. To make it worldwide, you've got to have a source of wealth in the villages to start with - tourism is not enough. That's where solar energy and biotech come in. Of course, it doesn't solve all the world's problems, of which population growth is Number One. But you have the feeling that once these places are gentrified, the birth rate will drop. It's happened everywhere else.

When the command economies broke, they broke fast, so the villages emptied out fast. Now we have a rampant market economy almost everywhere. It has enormous adaptive advantages, and many people are catching on to how self-organizing it is. But I suspect some are also beginning to encounter the extreme short-term thinking that goes with a market economy and its not-so-wonderful by-products.

Brian Eno says that the market economy is having trouble in places like Russia and Eastern Europe because they're moving straight to the rudest, crudest laissez-faire version, which looks a whole lot like crime. He says that the market economy doesn't work unless you have all the cultural framing that goes with it - things like trust, educational training, and going to college, which don't necessarily belong in a strict market economy.

As I've said before, I don't believe in the market economy. To me it's surprising it works as well as it does.

In your new book, *Imagined Worlds*, you say that Thomas Kuhn's account of paradigm shifts in science is only about *concept*-driven science. But you see science driven even more by *tool* revolutions. Can you give me some examples of that?

The Galileo revolution in astronomy was a prime example. The telescope was a tool that turned everything upside down. And X-ray crystallography turned biology upside down. The Crick-Watson discovery of the double helix was not a concept, it really was just the result of having a good tool to analyze the DNA molecule with. There's a chapter in my next book about John Randall, who was responsible more than any single person for the microbiological revolution. It's an interesting story. He was a third-rate physicist who had a very undistinguished career as a solid-state physicist in Birmingham. World War II had started and there was a desperate need for microwave transmitters. The English defense system was based on meter-wave radar, which was completely inadequate - and everybody knew it. If you wanted really good radar, you needed microwaves. So Randall was asked to invent a good microwave transmitter. It took him just two months. In November 1939 he invented the cavity magnetron. It absolutely revolutionized the whole state of the art. It was 1,000 times more powerful than any other microwave transmitter at that time. The device was the biggest contribution from Britain to the United States, given to them before the US even came into the war.

Is that what they were then working on at the Rad Lab at MIT? If so, they say it's what won the war.

Yes, the magnetron was actually invented in Birmingham, but they don't like to mention that. At the end of the war, Randall was a national hero. He was made Sir John and acclaimed as the savior of the country. After the war, he became a full professor at King's College London, with the prestige to do anything he liked. He decided solid-state physics was rather dull, and he wasn't very good at it anyway, so he decided to do X-ray crystallography with a view to applying it to biology.

In five years he built up this X-ray crystallography lab, where in 1950 Maurice Wilkins and Rosalind Franklin - the people who took the first images of DNA - produced pictures of X-ray diffraction in aligned fibers of DNA. It's what gave Crick and Watson their data. Nobody else in the world had that data.

Why wasn't Randall part of the Nobel Prize?

He organized the infrastructure. He wasn't the discoverer. That was fair. The question is, why didn't Rosalind Franklin get the Nobel Prize? Because Wilkins did. The real point I'm making is that it's rare for somebody to look that far ahead.

What are the next tool revolutions we need in science?

One is a DNA-sequence analyzer that sits on your table. There's a lot of hype about the Human Genome Project. Already we have about 100 identified genes associated with particular diseases, but it's all far too slow and expensive. It's ridiculous - you pay billions for one sequence, and it's not what the world needs. It's not sustainable. What you really want are thousands of sequences of all kinds of people with all kinds of diseases, and animals and plants. The goal is to sequence the whole biosphere. But the cost has to be reduced by a factor of 1,000 to make it worthwhile. The human sequence should be US$1 million or less - done on your desktop, about so big.

You're gesturing about a foot and a half square - it looks about the size of a scanning tunneling microscope.

It's the sort of device that will sequence the molecules one at a time so you don't have to do all this chemistry to multiply them and purify them. You simply take a single piece of a chromosome and sequence it as an individual molecule - using physics instead of chemistry.

Explain what you mean by "using physics instead of chemistry."

It's not a new idea to run a molecule of DNA through some device and physically chip off one base at a time. The four base types have different masses, so if you could detach them reliably, one by one, and run them through a mass spectrograph, it would take, maybe, a few microseconds to separate them cleanly.

It really is one molecule at a time. You're not talking reactions or anything here.

The present way of doing it is very ingenious, but it's wet chemistry - slow and extremely laborious.

If you could read DNA one base pair at a time, could you also manufacture it the same way using the same tool?

We don't know how to do that, but the synthesizers they have now are pretty good. Obviously, it would be nice if you could do it quicker. The lack of the analyzer is the bottleneck. No doubt synthesizers will keep on improving, but when you synthesize DNA, you want to synthesize fairly large quantities. Therefore, it automatically becomes chemistry.

What do we arrive at when we get that sort of reader?

We get the human genome for $1 million. We find out much more precisely the correlation between different medical conditions and different genes. We also find out much more precisely the evolutionary relations between humans and all kinds of creatures, all the way back. This whole business of genetic analysis is currently based on taking out little bits of DNA. If you had genomes of everything, it would be far more illuminating.

We could read history straight. We could date things.

It would be a tremendous breakthrough for both science and medicine.

The other tool, which is even more important, is a protein-structure analyzer. Most of the really important medical problems are concerned with proteins. The joke is that there are about 100,000 different proteins in each human cell - a minimum of what you want to know. But a few hundred thousand proteins is probably what we would like to have structures for to design drugs efficiently.

Presently we have done about 5,000 in 40 years or so. The first was identified by Max Perutz.

What was the protein?

Hemoglobin. Actually, myoglobin was done about a year sooner. Myoglobin was done by John Kendrew and hemoglobin by Perutz. They both won a Nobel Prize. It was a heroic effort. Since then, we've done about 5,000 more. Many labs are specializing in this area, but it's extremely laborious work. You have to crystallize the stuff before you can even start. And many of the important proteins are membrane proteins, which are noncrystallizable. They have very awkward shapes that are half inside the cell and half outside.

Reading structure must be different than reading base pairs.

Much harder. You're required to know the exact geometrical arrangement. The classical way to do this is by X-ray crystallography, and you can do a little with MRI (magnetic resonance imaging). Nowadays, most small proteins are done using MRI. But it doesn't work with the big proteins.

What's your sense of where other tools breakthroughs will happen?

One has already been invented by John Sidles at the University of Washington in Seattle. Sidles is a medical physicist. He works with the Department of Orthopaedics in the medical school, interpreting X rays and MRIs of shoulders and knees for a living.

In the evenings Sidles invents interesting devices for solving the problems of medicine. One of his inventions is called the magnetic resonance force microscopy (MRFM). There are two ways of looking at human tissues or molecules. One is magnetic resonance imaging, which has wonderful penetration. You can see everything inside your head but with very bad resolution. The other is the atomic force microscope, which is a very fine tip you scrape along the surface of a solid object to see individual atoms. You can measure the deflection of the tip with extraordinary precision; it's a wonderful device for looking at surfaces, but you can't see anything below. The point is to combine the resolution of the atomic force microscope with the penetration of the MRI.

John Sidles came up with a trick: instead of a mechanical tip, you use a tiny little speck of iron, a little ferromagnet suspended on this whisker of vibrating silicon that doesn't quite touch the surface. The iron speck creates a magnetic field that reaches into the interior of your sample. Under the surface you have atoms that experience magnetic moments. And you apply a radio field - in this case, an MRI machine - to flip the spins in the atoms up and down. These atomic spins then exert an up-and-down magnetic force on the iron tip. By matching the frequency of the magnetic force to that of the vibrating silicon whisker, you can then make the whisker vibrate enough to see the movement with a laser sensor. What you're seeing, then, is microscopy at the atomic scale. It looks very good to me. Of course, this is a prototype. The IBM Almaden Research Center in California built one and made it work. But it was only to demonstrate that the idea is OK.

What you've been talking about for the past 15 minutes sounds like nanotechnology , but you never use the term.

It's because I'm skeptical. Biotechnology has moved ahead so fast that it makes nanotechnology old hat. If we get to the point of building micromachines, it will probably be done by biotech.

At Global Business Network we're always looking for bifurcation points at which the world might go this way or that way because of some critical thing. One of the bifurcation points I've been proposing is the race between biotech and nanotech. Whichever gets "there" first affects everything else. If it's biotech, you have another couple decades of biology being the dominant metaphor for understanding the world. If it's nanotech, you have a more mechanical set of understandings. There is a kind of technological determinism to this. Once you've got a tool, it redefines the world, and you can't undo that.

I don't believe in technological determinism, especially not in biology and medicine. We have strong laws to keep doctors from monkeying around with humans that will remain in place. It's simply not true that everything that is technologically possible gets done.

Won't overseas labs that don't care about such matters show up soon and do all the forbidden things?

It's a question of how strongly the international community feels about it. On the whole, science remains amazingly international in spite of all sorts of wars and ideological disputes. We've never really had any communication breakdown.

You went to Biosphere 2 a couple of times. What's your sense of the value of that rather extravagant enterprise?

I was very enthusiastic about it. My first visit happened before they went in - when they were doing small-scale enclosure experiments, which I found more interesting than the big one. It would have been much more valuable to have had five or six small ones. You could find out what went wrong more rapidly and try out different approaches. Having just one is not good science.

As a work of art, it was great - the little rain forest, the lake, the farm, and various other ecological units. As a piece of science, it wasn't well designed. The second time I went, they were enclosed. All I could do was put my hands against the glass and exchange greetings on the telephone. But it seemed to be going quite well. Then they had a calamity, which was very satisfying to me - the fact that things turned out to behave in unexpected ways. The press castigated them because they ran out of air, but, to my mind, that meant it was good science because you found out something new.

Even the scientific press - until last year in Science magazine - said it was bad science, irrelevant, a blot on the escutcheon of science. You don't view it that way?

Biosphere 2 was much more than science; it was a human adventure. It was like the Apollo program, which wasn't really science either, but it had huge excitement attached to it and was a great sporting event. The science was simply an extra dividend.

Say something about failure in experiments or businesses or anything else. What's the value of failure?

You can't possibly get a good technology going without an enormous number of failures. It's a universal rule. If you look at bicycles, there were thousands of weird models built and tried before they found the one that really worked. You could never design a bicycle theoretically. Even now, after we've been building them for 100 years, it's very difficult to understand just why a bicycle works - it's even difficult to formulate it as a mathematical problem. But just by trial and error, we found out how to do it, and the error was essential. The same is true of airplanes.

This brings up an interesting issue of where theory fits in. Presumably there was not a theory of planes before there were planes.

There was an attempt at a theory of airplanes, but it was completely misleading. The Wright brothers, in fact, did much better without it.

So you're saying just go ahead and try stuff and you'll sort out the right way.

That's what nature did. And it's almost always true in technology. That's why computers never really took off until they built them small.

Why is small good?

Because it's cheaper and faster, and you can make many more. Speed is the most important thing - to be able to try something out on a small scale quickly.

Fail fast.

Yes. These big projects are guaranteed to fail because you never have time to fix everything.

One of the things I got from *Infinite in All Directions* - it was a delight to me, and I've been quoting it ever since - is that you honor inventors as much as scientists.

It's as great a part of the human adventure to invent things as to understand them. John Randall wasn't a great scientist, but he was a great inventor. There's been lots more like him, and it's a shame they don't get Nobel Prizes.

Is it the scientists who are putting them down?

Yes. There is this snobbism among scientists, especially the academic types.

Are there other kinds?

There are scientists in industry who are a bit more broad minded. The academics look down on them, too.

Is that a weird British hangover?

It's even worse in Germany. Intellectual snobbery is a worldwide disease. It certainly was very bad in China and probably held back development there by 2,000 years.

How would you stop this intellectual snobbery?

I would abolish the PhD system. The PhD system is the real root of the evil of academic snobbery. People who have PhDs consider themselves a priesthood, and inventors generally don't have PhDs.

Are those getting PhDs rewarded in any other way than as an honor?

It's much more than an honor. It's a ticket to a job.

So is anybody buying this? Are PhDs being abolished or disregarded?

No. The stranglehold has gotten even tighter over the years. It's become essentially like the MD - with much less justification. It's simply a barrier you have to climb over before you can make a career, and it's being imposed on more and more jobs. At even the smallest liberal arts college, nowadays, they say with pride, "All of our faculty have PhDs." Many of the best teachers are thrown out because they don't have a PhD. It's a paper qualification that poisons the whole field.

What you're saying reminds me of a situation a couple of years ago when my colleague at GBN, Peter Schwartz, and I tried to do a book called *Biofutures*. When we started to research the future of biotechnology, we found an interesting contrast with the computer world. You can't get computer people to shut up about the future. They go on and on about it. In biotech we couldn't find anybody who *would* talk about the future.

There are a couple of interesting components to this. First is the government regulation you speak of, which has good reason for being in place because of the life-critical issues, deep cultural issues, and so on. The result is, of course, that when any of the researchers start talking out of school, saying, "Well, maybe we'll cure death," that's it - they don't get the money, because they're obviously "irresponsible."

The second component of this idea brings me on to your point about PhDs. Because of the whole realm of government permissions and grants surrounding biotech, it's attracting more PhD types and fewer amateur types, whereas computer technology tremendously enables amateurs.

What also strikes me is that the culture we see here [at the PC Forum, the annual computer conference run by

Dyson's daughter Esther] is far friendlier to women than the academic world I come from; it's largely because you don't have to have a PhD. You don't even have to have an MBA to run a company. Many of these women, in fact, start young, own their own companies, and are doing well at the age of 25. They then have plenty of time to raise a family if they feel like it. It doesn't interfere with their careers.

In academic life, it is a terrible problem. Women are forced to go through this PhD rigmarole, which takes far too long. By the time they get the PhD, they're already middle aged, and then the problems of trying to combine a career with a family become really fierce. To me, that's the greatest evil - that women are discriminated against much more as a result of this. I love it when I come to these meetings of computer people. The women are really going ahead, and there's a higher fraction of them, and they're much less inhibited.

Especially your daughter. Esther has been a funny kind of pioneer: an observational and analytical pioneer in this field. She doesn't write code.

No, but she's typical in the sense that she got ahead without bothering to take an MBA.

You can see the great affection in which she's held by this large and significant community. What are the origins of that? She's the child of a scientist and a mathematician. What was her education like? How do you make an Esther Dyson?

The main advantage she had was being neglected. We had two other children, one older and one younger, who were real problems. She wasn't a problem, and so she didn't get much attention. She always knew what she wanted, and she was very quiet and easygoing.

But you would do things like encourage her to study Russian in high school.

It wasn't only my encouragement. She had a very good Russian teacher in the school, and, of course, she loved the language.

This is clearly an unusual school, or is it?

It's an ordinary public school, but he was an unusual teacher. He's still there, by the way.

This is where?

Princeton High School. I think he normally teaches French, but he happens to be of Russian extraction.

I understand that you were interested in Russian because of Russian literature. How did you find out about that?

It was from my mother, who had a Russian dictionary in the house. She had studied the language in World War I, when Russia was allied with England. I was always curious about languages and words, and this Russian dictionary was one of the books I loved to browse, especially because it had the old orthography, dated from 1916.

Where did Esther go to college?

Harvard.

Did she try for any degrees after that?

No. This is one of the old chestnuts I'm always telling my friends about. I visited Estie at Harvard. I decided that I would just go and see what she was doing there. She was rather young, an undergraduate. I stayed for three or four days. She spent all of her time at *The Harvard Crimson*, the student paper she was writing for, and as far as I could see she never did any studying or went to classes. As I was about to go back to Princeton, I thought I would have a little talk with her and play the heavy father. So I said, "You know, I am paying tuition for you. And I find it a little bit surprising that you don't seem to do any studying."

She told me, "Oh, no, Daddy, you don't understand. You don't come to Harvard to study. You come to Harvard to get to know the right people." That's exactly the secret of her success, of course. That's why she can run these meetings. She knows everybody by sight, and that's not trivial. She really is interested in all those 500 conference people as individuals. It's also why she's good in the venture-capital business. She says, "To know whether a venture is worth supporting, you have to get to know the people - everything else is secondary." She's more interested in the people than in the technology - that's always been true.

Did she get decent grades at Harvard?

I don't know.

And clearly nobody cared. They didn't kick her out, at least.

Harvard was ideal for her because they don't care about the undergraduates. It's essentially a graduate school; the undergraduates are left to sink or swim.

I'm on a couple of boards with Esther, at the Santa Fe Institute and Global Business Network. I've seen her come to trustee meetings at the Santa Fe Institute, and she'll arrive a half day early and hang out with the staff, so by the time she shows up at the board meeting, she knows all the gossip. She did the same thing at Global Business Network. I asked her about this: "That's a pretty interesting heuristic you've got there, because there's supposed to be a barrier between board members and staff, but you break that down and you make it work for you." She said, "Well, I learned to care very much about staff people. That's where the action is, and I learned that all from my father." I'm curious. What is she talking about?

That is strange to me. I would say she got it from her grandfather. I never was good with people, and I never tried to be an administrator. I've always preferred to live my own life. I may respect staff people, but I don't go out of my way to be friendly to them or to learn the gossip. My father did, though.

I don't know much about your father.

He was a musician who became a very successful administrator; he ran the Royal College of Music. My father was in a very powerful position because he was head of the British musician's union as well as head of the music conservatory.

He was both management and labor.

Yes, and he cared tremendously about staff people. He always said, "As long as the cooks are comfortable, the college will do well." He came from a working-class background himself. I may have talked about him to Estie quite a lot because I always respected him. He also had written his autobiography - *Fiddling while Rome Burns*, by George Dyson. It reveals a lot about him and the way he looked at things.

There's a provocative sentence in *Imagined Worlds*: "The laws of nature are constructed in such a way as to make the universe as interesting as possible." What do you mean by that?

It's the numerical accidents that make life possible. I define an interesting universe as one that is friendly to life, and especially one that produces lots of variety.

What accidental numbers make that possible?

If you look at just the physical building blocks, there's a famous problem with producing carbon in stars. All the carbon necessary for life has to be produced in stars, and it's difficult to do. This process was discovered by Fred Hoyle. To make carbon, you've got to have three helium atoms collide in a triple collision. Helium has an atomic weight of 4, and carbon is 12, while beryllium, at 8, is unstable. Therefore, you can't go from helium to beryllium to carbon. You have to make helium into carbon in one jump; this means the three colliding together.

Which statistically is not so often.

No. But Hoyle came up with one of the most brilliant ideas in the whole of science. He said that in order to make carbon abundant as it should be, there must be an accidental, coincidental resonance. This means that there's a nuclear state in the carbon nucleus at precisely the right energy level for these three atoms to combine smoothly. The chances of having that resonance in the right place is maybe 1 in 1,000. Hoyle believed it must be there in order to produce the carbon. Of course, the nuclear physicists then looked for this resonance and found it!

There are other famous cases: the fact that the nuclear force is just strong enough to bind a proton and a neutron to make the heavy isotope hydrogen but not strong enough to bind two protons to make helium with an atomic weight of 2. Just two protons stuck together is a rather narrow range of strength. So the nuclear force is fine-tuned so that hydrogen doesn't burn to helium right away. If the two hydrogen nuclei did bind, all the hydrogen would burn to helium in the first five minutes. The universe would then be pure helium and a rather boring place. Whereas, if the force were a little bit weaker, so that the neutron and the proton didn't bind, you wouldn't get any heavy elements at all. You'd have nothing but hydrogen. Again, this would make for a boring universe. You can argue as to how significant these things are, but it looks as though the universe was intended to be as interesting as possible.

So this is what you mean by cosmic ecology. I can see why you're sympathetic toward the Gaia hypothesis of Jim Lovelock and Lynn Margulis.

It makes a great deal of sense.

Why has it got such a bad reputation among scientists?

It's this old hangover from the 19th century, when the biologists had to fight against the orthodox Christian beliefs.

Are they afraid it's mysticism? Or is it vitalism or one of those old bugaboos?

It goes against the dogmatic belief that biology has to be mechanistic. I'm surprised that biologists, on the whole, are so mechanistically inclined. It's very striking.

I was trained as a biologist, and there has been a sequence of interesting mistakes in biology. Vitalism may have been one. The ideas of climax and self-defending ecological communities had a sort of superorganismic quality to them, which turned out to be illusory. Then you have people like Richard Dawkins come along and say, "Well, it's not even the damned organism. It's gene by gene." So, in a sense, the reductionist, mechanist approach has been rewarded, and the holistic approach has been punished.

My cybernetics training came straight from reading Norbert Wiener, but these days, we're seeing a gradual return of what is now called not cybernetics, but complexity theory. It's coming back via the computer route because you can model things richly in computers, so it's OK to start thinking systematically again. For some reason, that hasn't made the jump to Gaia.

A lot of the prejudice against Gaia comes from the way it's been hyped. It's got a lot of unsavory associations that really are mystical.

Of the books you're reading, the stuff you're listening to, and the people you're paying attention to, what percentage are scientists and what percentage are from the humanities?

The great majority are scientists.

You know a lot of poetry and music also.

Yes, but I haven't been keeping up. Lately, I've become a tame scientist for the theologians. I get invited to a number of meetings on what they call "Science and Religion" or "Science and Theology," and I talk with theologians. I don't find it very helpful. I take my religion without theology.

What does that mean, you take your religion without theology?

Most religion in the world doesn't have theology. Theology is something very peculiar to Christianity. It didn't even come from Jesus. It was an accident. The Greek world was heavily philosophical at the time Christianity was developing, and so the Christians adopted all this jargon from Greek philosophy and incorporated it into their religion; that became theology. I've never found it essential to my religion or to other religions. Judaism has practically no theology, and Islam has very little - Buddhism, even less. It's given rise to this profession of theologians who would like to make the subject into a science, particularly John Templeton. He organizes these conferences I go to, and he has a strong belief that he can make theology scientific and make religion into a force for progress.

What is your religion?

Christianity, but of a very watered-down kind - essentially, what's left over after you get rid of the theology. The Church of England is pretty close to it.

You say in *Imagined Worlds* that the two human institutions that can think about long-term issues are science and religion. And you raise the question in the book - a little more than you answer it - of long-term ethics. It's an area that I'm acutely interested in. How might long-term ethics differ from ethics as we generally understand them?

If you mean balancing the permanent against the ephemeral, it's very important that we adapt to the world on the long-time scale as well as the short-time scale. Ethics are the art of doing that. You must have principles that you're willing to die for.

Do you have a list of these principles?

No. You'll never get everybody to agree about any particular code of ethics.

But if they're going to be long-term ones, you'd better have some agreement. This is a cross-generational issue. It's caring for children, grandchildren. In some cultures you're supposed to be responsible out to the seventh generation - that's about 200 years. But it goes right against self-interest.

I'm working on a project, The Long Now Foundation, to encourage long-term responsibility. Esther's on that board, too. We're building a 10,000-year clock, designed by Danny Hillis, and we're figuring out what a 10,000-year library might be good for. If the clock or the library could be useful to things you want to happen in the world, how would you advise them to proceed? For instance, if you want to see humanity move gracefully into space, you have to accept it's going to take a while.

I'm accustomed to living among very long-lived institutions in England, and I'm always surprised that the rest of the world is so different. At the beginning of *Imagined Worlds*, I mentioned the avenue of trees at Trinity College, Cambridge. It is an extremely wealthy foundation, founded by Henry VIII with the money he looted from the monasteries. He put his ill-gotten gains into education, much to our benefit. So we pray for his soul once a year. I went to the commemoration feast last March and duly prayed in appropriate Latin. Trinity is an astonishing place because it has been a fantastic producer of great science for 400 years and continues to be so. Beside Henry VIII, we were celebrating the 100th birthday of the electron, which was discovered there by J. J. Thomson. He was appointed professor at the age of 28.

Anyway, they planted an avenue of trees in the early 18th century, leading up from the river to the college. This avenue of trees grew very big and majestic in the course of 200 years. When I was a student there 50 years ago, the trees were growing a little dilapidated, though still very beautiful. The college decided that for the sake of the future, they would chop them down and plant new ones. Now, 50 years later, the new trees are half grown and already looking almost as beautiful as the old ones. That's the kind of thinking that comes naturally in such a place, where 100 years is nothing.

It must be harder to keep the science fresh than it is to keep the trees fresh.

Somehow they're able to do both. It's the habit of long-term thinking that has made this possible. It survives all over England. It's one reason the country has been so amazingly well cleaned up after the Industrial Revolution. The worst pollution in the world was in England.

I didn't know that.

When I was a boy, I went to London, and my clothes were filthy at the end of the day. The city was covered with soot and grime, and the rivers were very polluted; it's all been cleaned up in the past 50 years. You can always improve things as long as you're prepared to wait.

So it's patience.

Lots of patience. The famous story goes, "How do you make these beautiful British lawns?" and the answer is, "Oh, you just roll them for 200 years." They've never thought of things in terms of quick returns.

Now, science is all about change and intellectual revolutions. That's what keeps everyone excited about it. It's the real news. You have here in the US, and at Trinity College, scientific revolutions that are dependent on turning over the previous constructs of the universe, yet here's an entity - science - that has existed inside those buildings for a very long time and expects to be in those buildings for a very long time. How do you reconcile that match?

It goes naturally together. You need the space of continuity to have the confidence not to be afraid of revolutions.

So you can throw away some stuff because there's a lot of other stuff that will be there?

Yes. It's like having a life-support system. In scientific terms, it's what you'd call indirect development of embryos, now understood to be common in the evolution of the higher organisms. First you have an embryo, and this embryo sets aside a package of cells that become the adult - the rest of the embryo serves only as a life-support system for the adult as it grows. It's called indirect development because there's absolutely no connection in structure between the embryo and the adult.

Can you give me examples?

Primitive creatures like sea urchins and almost anything apart from vertebrates and insects. The adult can experiment with all sorts of marvelous new patterns of development, being assured of life support from the embryo. You might say it's a metaphor for Trinity College.

Speaking of academia, you've been at the Institute for Advanced Study for 45 years. It's interesting that you're in America and not at Trinity.

The institute has treated me very generously, and in many ways it is ideal for me.

Remind me a little of how it functions for most people at the institute.

It's a motel with stipends. We provide all the amenities, the most important being a nursery school, apartments for the families, a place to eat, an office and a computer terminal, and a stipend. People come from all over the world, and they stay a year or two and they do whatever they like. It's about half humanities and half science. The place is an international meeting ground. It's about the only place where somebody not fluent in English with a family even less fluent can feel comfortable, because we don't demand that they teach. It's not what they produce while they're at the institute. It's much more important that they get a chance to find out what's going on in the world and take it back home with them. They do the immortal work after they get back.

Related question: How do you know what to work on next?

It's always a gamble. The general rule I tell people is: "While you're young, work on the fashionable stuff -

that's where you get ahead fast and make a reputation. When you're older, do the unfashionable things that, in the end, may be more important but that won't get you recognized right away."

For myself it's always rather opportunistic. I have a short attention span, so I tend to just look around for interesting puzzles and work on anything that strikes me as being amusing. In that way I'm different from Francis Crick, who always looked for the most important things to do.

How can you tell when something's interesting?

It's a matter of aesthetics. I was trained as a mathematician. My tools are mathematics, so if it's elegant mathematics, that's all I care about, and if it also happens to be useful, so much the better. I just published my collected technical works. There's an awful lot I've done that is not worth preserving. I never really went for the important things, but I'm not sorry about that. I still did enough that was interesting.

People who read *Wired* are young and optimistic, and they're probably aware of Dyson spheres in science fiction, and if they read your books they see there's a lot of off-planet activity in store. What should they be doing to get off-planet?

Biotechnology is what it takes - especially if we're talking about people getting off-planet, rather than just scientific exploration. I'm already thinking about my next book about freeze-dried fish and warm-blooded plants. That's the way to look for life on other planets. Look for what's detectable and not for what's probable. This has always worked in astronomy.

Examples?

The planets around a pulsar discovered by Alexander Wolszczan - a marvelous discovery. Everybody believed that there couldn't be planets around a neutron star, including Wolszczan. But that's the only place where a planet of Earth's mass is detectable - therefore, he discovered them.

It sounds like another case of the universe trying to be interesting.

Europa's ocean is interesting. It's most likely a liquid ocean, warm and very deep. Europa's the second satellite out from Jupiter. The inner satellite, Io, is blazing hot; it has volcanoes. The other satellites are frozen solid. In between there's Europa, which has a thin layer of cracked ice. If you want to find creatures living in Europa's ocean, you can do it the hard way - send a huge spacecraft carrying a submarine, dig through the ice, then launch the submarine to explore the ocean. Or you can do it the easy way. We know the other satellites have huge numbers of craters from being close to the asteroid belt. So what happens when Europa is hit with a huge asteroid? It will splash out immense quantities of water into space. If there are any fish present, they will be kicked out and freeze dried, and you'll find them orbiting around Jupiter. There is already a ring of debris orbiting Jupiter, but nobody has gone to see if there are any freeze-dried fish. It's a clever way to explore.

Similarly with Mars. What would you expect to find living on Mars? The conventional view is microbes. They live deep underground, where it's warm and wet. So, to find life, you have to send a huge drilling operation. But it's not the right way to do it, because underground microbes are hard to detect. Instead, look for something easy to detect, like warm-blooded plants. These are plants that grow their own greenhouses. They simply sit on the surface and grow small organic windows and lenses outside that focus sunlight in.

How do you find them? You just look at night for warm patches. If you don't find any warm-blooded plants already there, you grow them yourself and seed them on Mars or Europa or anywhere else - as long as there's a sun within an enormous distance. It could go way beyond Pluto.

Sounds great.

That's the future of human exploration in space. We've got to wait for the biotechnology. Anything you do with conventional spacecraft and space suits - all this living in tin cans - is uninteresting and far too expensive.

Have you read a book called *The Case for Mars*?

Yes.

What do you think of Zubrin's argument?

I'm not interested in anything that expensive.

Not even $5 billion.

My limit is $1 billion for projects of that kind. There will be lots of cheap propulsion systems.

Twenty years from now?

Probably longer. I don't find space travel interesting unless it's cheap. The whole point is to make it available to ordinary people. I give it a hundred years for large-scale emigration to be cheap enough. I'm not in a hurry. I think it's interesting that you can do it at all.

Notes

Robert L. Forward A technologist, science fiction writer, and consulting scientist specializing in exotic physics and advanced space propulsion. (www.whidbey.com/forward/) Back

Vernor Vinge An associate professor of mathematical and computer sciences at San Diego State University who specializes in computer architecture and distributed systems. (www-rohan.sdsu.edu/faculty/vinge/misc/singularity.html) Back

Moore's Law A principle first stated in 1965 by Intel cofounder Gordon Moore, who predicted that the number of transistors on a chip would double every 18 months. Back

Teledesic Network A proposed constellation of several hundred low-Earth-orbit satellites. Teledesic, headed by Craig McCaw, is backed by Microsoft and The Boeing Company; the firm is headquartered in Kirkland, Washington. Service is due to begin in 2002. (www.teledesic.com/) Back

Command economy An economy that relies on a centrally controlled command structure. Rare examples today include North Korea, Cuba, and China. Back

Brian Eno A musician, artist, and producer, and the father of ambient. Among his collaborators: U2, David Bowie, and the Royal College of Art. (eno.sb.org/) Back

Thomas Kuhn A science historian and the author of *The Structure of Scientific Revolutions* (1962). His concept of paradigm shifts was later adopted by political scientists, economists, and business managers alike. Back

X-ray crystallography The determination of the detailed spatial location of each atom in a crystallized molecule. Back

Maurice Wilkins A physicist who worked on the atomic bomb at the University of California at Berkeley during World War II. Wilkins shared the 1962 Nobel Prize in medicine with Francis Crick and James Watson. Back

Crick and Watson The team of Francis Crick and James Watson, who in 1953 determined that the structure of DNA is a double-helix polymer. DNA was first discovered in 1869 but was not linked to genetic research until 1943. Back

Human Genome Project A scientific undertaking sponsored by the US Department of Energy and the National Institutes of Health to identify the chromosomal location and chemical structure of every human gene. (www.ornl.gov/TechResources/Human_Genome/) Back

Scanning tunneling microscope A microscope with sufficient resolution to detect a single atom. It "feels" an atom rather than sees it, registering the variation of electrons on a sample's surface to determine the shape of its features. Back

DNA synthesizer An instrument used for the automatic production of defined-sequence oligodeoxyribonucleotides (single strands of synthetic DNA) from reservoirs of base-pair solutions. Back

MRI Magnetic resonance imaging, the response of magnetic fields to radio-frequency waves to produce computer images that provide important structural and biochemical information about tissue. Safer than X-ray imaging and often used to detect cerebral edema and cancer. Back

Almaden Research Center A Big Blue facility in San Jose, California, where approximately 500 employees focus on data-storage systems and advancements in material sciences. Back

Nanotechnology The development of mechanical devices on a nanometric (billionth-of-a-meter) scale - the size realm of individual molecules. The term was first proposed by K. Eric Drexler in *Engines of Creation* (1986). (www.scicentral.com/E-nanote.html) Back

Global Business Network A futurist consulting network in Emeryville, California, specializing in scenario planning for large organizations. Members are drawn from high tech, the sciences, the arts, and academia. (www.gbn.org/) Back

Biosphere 2 A sealed glass-and-steel structure in Oracle, Arizona, covering 3.15 acres. Inside this ecological experiment, scientists have created seven biomes imitating those of Earth - an ocean, a desert, a savannah, a rain forest, a marsh, an agricultural area, and a human habitat. Begun in 1984, the project is designed to last 100 years. (www.biospherics.org/biosphere2.html) Back

Bicycles The first two-wheeled, rider-propelled machine on record is the draisienne, invented by Baron Karl de Drais de Sauerbrun and exhibited in Paris in 1818. Myriad prototypes followed until the late 19th century, after which the basic mechanical structure remained constant. Back

Peter Schwartz The cofounder and chair of Global Business Network and author of *The Art of the Long View* (1991). Back

PC Forum Esther Dyson's annual four-day computer conference, where industry leaders and visionaries discuss new directions in the technology business. Back

Esther Dyson The president and majority owner of EDventure Holdings, a company focused on emerging information technology worldwide. Editor of *Release 1.0*, a monthly technology newsletter, and author of *Release 2.0* (1997). (www.edventure.com/bios/esther.html) Back

Orthography The art of writing words according to standard usage, or the representation of the sounds of a language by written or printed symbols. Back

Santa Fe Institute A nonprofit research and education center, founded in 1984 in Santa Fe, New Mexico, that specializes in the interdisciplinary study of complex systems. (www.santafe.edu/) Back

Fred Hoyle A British mathematician and astronomer who, in 1948, with astronomer Thomas Gold and mathematician Hermann Bondi, announced the steady-state theory. The theory holds that the universe is expanding and matter is being continuously created to keep the mean density of matter in space constant. Back

Gaia hypothesis A theory named by British chemist James Lovelock and American biologist Lynn Margulis after Gaia, the ancient Greek goddess of the earth. In Lovelock's words, it's "a new insight into the interactions between the living and the inorganic parts of the planet. From this has arisen the model in which Earth's living matter, air, oceans, and land surface form a complex system that can be seen as a single organism and that has the capacity to keep our planet a fit place for life." Back

Lynn Margulis The author of *Symbiosis in Cell Evolution* (1981), in which she proposes that three types of prokaryotes (simple organic structures) fused biologically to create the first living cells with nucleic structures. Back

Vitalism A school of scientific thought - dating back to Aristotle - that attempts to explain life as the result of a vital, almost mystical force unique to living organisms. Back

Richard Dawkins A zoologist who wrote *The Selfish Gene* (1976), in which he argues that natural selection takes place not on the level of the individual, but rather among genes. These, he maintains, use the bodies of living things to further their own survival. He also introduced the concept of memes - self-replicating ideas. (www.spacelab.net/~catalj/) Back

Cybernetics A science based on the dynamics common among living organisms, machines, and organizations. (www.gwu.edu/~asc/) Back

Norbert Wiener A mathematician who established the science of cybernetics in *Cybernetics, or Control and Communication in the Animal and the Machine* (1948). Back

Complexity theory Analysis of the interactions between the many parts of a system. The study includes aspects of chaos theory, evolutionary theory, and self-organization theory. Back

John Templeton A financial wizard who founded the John Templeton Foundation in 1987 to explore the relationship between science and religion. The foundation grants the US$1 million Templeton Prize for Progress in Religion. (www.templeton.org/) Back

Church of England An institution that traces its history to the arrival of Christianity in Britain during the second century. In 1534, King Henry VIII issued the Act of Supremacy, which signified his country's break with the Catholic Church of Rome. Back

The Long Now Foundation A nonprofit organization established in June 1996 to encourage long-term thinking and responsibility. Current projects include the 10,000-year Clock and Library. (www.longnow.org/) Back

Danny Hillis The cofounder and former chief scientist of Thinking Machines Corporation (now at Walt Disney Imagineering), who pioneered the concept of massively parallel computers. Back

Sea urchin Any of about 700 living species of echinoid marine invertebrates (phylum Echinodermata) with a body of five bands of pores running over the entire internal skeleton. Back

Institute for Advanced Study A private institution founded in Princeton, New Jersey, in 1930 to promote learning through research and scholarships across many fields. Attracted some of the world's most respected thinkers this century - including Albert Einstein. (www.ias.edu/) Back

Collected technical works *Selected Papers of Freeman Dyson: With Commentary* (1996). Dyson's most important technical papers of the last 50 years, with his background notes on subjects ranging from number theory, topology, and quantum electrodynamics to random matrices, adaptive optics, and interstellar communications. Back

Dyson spheres A shell, proposed by Freeman Dyson, that could be used by an advanced civilization to harness a substantial amount of a star's energy by enclosing it in a shell, thereby capturing most of the radiation emitted. He originally proposed an artificial biosphere, a habitat that could be any shape and could consist of any number of pieces. Science fiction writers have since modified the idea to make a Dyson sphere one rigid shell. Back

Bibliography

Disturbing the Universe Largely autobiographical work in which Dyson shares his understanding of the laws of the universe (Harper & Row, 1979).

Weapons and Hope Dyson's framing of nuclear weapons in the larger historical context of humans at war (Harper & Row, 1984).

Origins of Life Based on Dyson's philosophical lecture about life's origins at Cambridge University's Trinity College (Cambridge University Press, 1985).

Infinite In All Directions A culmination of Dyson's lectures on "the diversity of the natural world, and the diversity of human reactions to it" (Harper & Row, 1988).

From Eros to Gaia A series of sweeping essays about the people and events of 20th-century science (Pantheon Books, 1992).

Selected Papers of Freeman Dyson: With Commentary The most important technical papers of Dyson's scientific career to date (American Mathematical Society, 1996).

Imagined Worlds Dyson's critically optimistic overview of how science and technology tools can sustain civilization deep into the future (Harvard University Press, 1997).

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