what we get are totally different from ribosomes in step #3. If this happens, then that, I would say, is strong evidence that we should expect to have life in all sorts of places, involving all kinds of different ways of living other than having ribosomes.

SASSELOV: That's the question of multiple versus simple pathways to life. Just answering that question would be essential.

LLOYD: And that's quite possible—even if it's too hard to figure out exactly how life originated on Earth. This is a much easier question, I think, to answer than the question of how did life exactly originate on Earth. Because there you have to figure out the exact initial conditions for this complicated set of chemical reactions, and that's going to be hard.

SHAPIRO: And the other point of view has been very much pushed over the ages; I think George Wald once said that if you study your biochemistry text on Earth you can pass examinations on Arcturus. Which is a star somewhere out there—and this is essentially saying the opposite.

9
The Gene-Centric View: A Conversation

Richard Dawkins & J. Craig Venter

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Introduction by John Brockman

It's not every day you have Richard Dawkins and Craig Venter on a stage together. Richard Dawkins is responsible for possibly the most important science book of the last century, *The Selfish Gene*, published in 1976, which set forth an agenda of the gene-centric, or gene's-eye-view of life, which has become the basic science agenda for biologists for the last quarter century. And without that worldview, you wouldn't have Craig Venter changing the world the way he is today. Venter led the private group that decoded the human genome in 2001. He's working on the forefront of artificial life, synthetic biology. He's traveling around the world on a sailboat, finding millions of new genes in the oceans. Most recently, his lab was responsible for transplanting the information from one genome into another. In other words, your dog becomes your cat. What we'll present first is a conversation between Craig and Richard, and then they will entertain questions.

The Gene-Centric View: A Conversation

RICHARD DAWKINS: I thought I'd begin by reading a quotation from a famous philosopher and historian of science from the 1930s, Charles Singer, to give an idea of exactly how much things have changed. And Craig Venter is a leader—perhaps *the* leader—in making that change today. Here is Singer, in 1931: "Despite interpretations to the contrary, the theory of the gene is not a 'mechanist' theory. The gene is no more comprehensible as a chemical or physical entity than is the cell or, for that matter, the organism itself. . . . If I ask for a living chromosome, that is, for the only effective kind of chromosome, no one can give it to me except in its living surroundings any more than he can give me a living arm or leg. The doctrine of the relativity of functions is as true for the gene as it is for any of the organs of the body. They exist and function only in relation to other organs. Thus the last of the biological theories leaves us where the first started, in the presence of a power called life, or psyche, which is not only of its own kind but unique in each and all of its exhibitions." You couldn't ask for a more comprehensive destruction of a conventional view than that. That is not just wrong, it is catastrophically, utterly, stupefyingly wrong. It's wrong in an interesting way, and Craig is the best person to tell us what's wrong with all that.

J. CRAIG VENTER: I feel like this is a quiz, Richard [laughter]. Richard's book *The Selfish Gene* influenced most thinking in modern biology. I actually didn't like his book, initially—I've never told him that. But I've come to appreciate it immensely. I was looking at the world from a genome-centric view—the collection of genes put together to lead to any one species—but as we traveled around the world trying to look at the diversity of biology, we came up with larger and larger collections of genes. We now have a database of roughly 10 million; that number will probably double again, this year, to 20 million.

To put it in context, we humans have only around 22,000 genes. We represent sort of a minority in the usage of genes on this planet. But I've switched, and I've come to view the world

from a gene-centric point of view—in part because we're now going into the design phase. I'm looking at genes as the design components of the future, not just as interesting elements of biology. I now look at genomes as interesting composites of genes. But we have almost an infinite variety that we could put together to create biological machines of the future. Unlike that quote from Singer, chromosomes *can* exist independently. Genes *can* exist independently. They can move around independently.

Last year, we isolated the chromosome from one bacterial species and transplanted it into another. The chromosome in the species we transplanted into was destroyed, and all the characteristics of one species went away and got transformed into what was dictated by the new chromosome. It's sort of the ultimate test in proving that this is the information of biology and dictates what a cell can do and maybe even should do. This was a precursor to being able to design life—build synthetic molecules by looking at individual genes. We now have some gene families where we have 30,000, 40,000, 50,000 members—natural variants that occur in the population. And we have major problems we're trying to overcome in modern society by looking for solutions.

The first uses we're looking at is trying to come up with alternate ways of making fuel. Instead of taking carbon out of the ground, given this diversity of biology, we have thousands, perhaps tens of thousands, of organisms that can take the energy from sunlight and carbon dioxide from the environment, fix the carbon from the carbon dioxide, and also make a potential fuel—natural gas, such as methane. When we look at cells as machines, it makes it straightforward in the future to design them for unique utility. All these advances speak against that one quotation.

DAWKINS: It's more than just saying you can pick up a chromosome and put it in somewhere else. It is pure information. You could put it into a printed book. You could send it over the Internet. You could store it on a magnetic disk for 1,000 years, and then, in 1,000 years' time, with the technology we'll have then, it will be possible to reconstruct whatever living organism is here now. This is something utterly undreamed of before the molecular information revolution.

What has happened is that genetics has become a branch of information technology. It is pure information. It's digital information. It's precisely the kind of information that can be translated digit for digit, byte for byte, into any other kind of information and then translated back again. This is a major revolution. I suppose it's probably *the* major revolution in the whole history of our understanding of ourselves. It's something that would have boggled the mind of Darwin, and Darwin would have loved it, I'm sure.

VENTER: Well, to speak to this: For the past fifteen years, we've been digitizing biology. When we decoded the genome, including sequencing the human genome, that was going from the analog world of biology into the digital world of the computer. Now, for the first time, we can go in the other direction. With synthetic genomics and synthetic biology, we are starting with that purely digital world. We take the sequence out of the computer and from four raw chemicals that come in bottles we can reconstruct a chromosome in the laboratory, based on either design: copying what was in the digital world or coming up with new digital versions. In fact, somewhat jokingly, I can argue that this is the only nanotechnology that actually works. Biology is the ultimate nanotechnology, and it can now be digitally designed and reconstructed.

DAWKINS: There are people who are uneasy about this kind of science. They sometimes call it scientism. And there's a certain suspicion of arrogance. The phrase "playing God" has been brought up. I don't think I have a problem with that, but I think it's something we ought to take seriously. What I do have a problem with is the possible unforeseen practical consequence of some of the sorts of things that not just you but many people are doing. I suspect that the phrase "playing God" is actually a kind of—it's a bit like the boy who cried wolf, because accusing a scientist of playing God is obviously stupid. But what is not obviously stupid is accusing a scientist of endangering the future of the planet by doing something that could be irreversible. We may become so used to fending off idiotic accusations of playing God that we might overlook the real dangers. Do you think that's a possible danger?

VENTER: It's a real-life danger that we're facing now. I've argued that we are now 100 percent dependent on science for the survival of our species. In part, the science of today has to overcome the scientific breakthroughs of previous years. Because we have advanced internal combustion engines; because we're so good at burning carbon that we take out of the ground; we did it blindly, without any [thought of the] consequences, that it might totally affect the future of the planet.

We can replace the carbon we're taking out of the ground by renewable sources, and the best renewable source we have is energy from the sun. Over 100 million terawatts a day hit the Earth. We have cells that capture carbon back from the environment. And it turns out, chemically and biologically in the lab, we can make anything in the lab that comes out of the ground, in terms of carbon. We can make octane. We can make diesel fuel. We can make jet fuel. We can make butanol. Ethanol—humanity's been doing that forever, through simple fermentation.

These ideas are slow to catch on. People are much more concerned that there might be new consequences of engineering biology than about this potential disastrous route we're on—totally changing our atmosphere, maybe making it impossible ultimately for our species to survive. That's a far more dangerous experiment.

DAWKINS: Did I understand you to be saying that whereas the energy we get out of the ground—oil and coal—took millions of years of all those terawatts of sunlight hitting leaves in the Carboniferous and being stored, do I understand you to be saying that now, with the biotechnology you're doing, it should be possible to capture those terawatts of energy on the fly, as it were, and use them in the present, rather than [using what's been] stored over millions of years from the past and dug out of the ground?

VENTER: Exactly. What we're doing with burning oil and coal is we're taking millions of years of compressed biology, we're burning that over the course of years and putting it into the atmosphere. We can do just the opposite. We can even capture back some of that CO_2. It only takes about 1 percent of the sunlight that hits the Earth daily to replace all the fuel we use, all the energy we use for transportation. These are not huge leaps. There's just been no motivation for it, because oil was cheap. We've gone through this cycle, twice now, where people rapidly pursued alternate energy sources and then the cost of oil dropped. In fact, that's my biggest concern. The price of oil is in the hands of a very few people. And if there's truly alternatives that come on the market, the cost of oil could be artificially dropped to really low prices, killing off these essential new industries. The way

forward, in a political sense, is there has to be a carbon tax on nonrenewable carbon to disincentivize people from burning it. Even the Bush administration recognizes that we're in the realm of climate change due to carbon going into the atmosphere. If *they* understand it, the rest of the world can.

BROCKMAN: At the "Life, What a Concept!" meeting, Freeman Dyson basically challenged Richard by saying that evolution is now back to the prebiotic stage of communal, horizontal gene transfer, and with the interlude of what he would call the "Darwinian moment." Richard rebutted that in an e-mail, which is rather exciting reading. But the question I have is: Dyson maintains that evolution is now man-made—cultural rather than Darwinian. Is it?

VENTER: All evolution is based on selection. We, as a species, have been affecting the direction of evolution for some time, whether we wanted to or not, by changing the environment. Now we can do it in a deliberate, hopefully thoughtful fashion, by deliberate design. But that deliberate design still has to be followed by selection.

When we look at that experiment we did, transplanting a genome from one species to another, many people who try to argue against evolution on religious grounds stick to this point-mutation and selection mode, the most limited version of Darwinian evolution, to argue how complexity couldn't occur from that. But what we see with chromosome transplantation is, we can get a million changes in a species in an instant. And not only does this happen just by our work in the lab. Looking back in history, we see major species evolution from species taking on new chromosomes. When they take on a new chromosome, it's like adding a new DVD full of software to your computer. It instantly changes the capabilities and the robustness of what you can do. Our cells can do that. We have real-time Darwinian evolution taking place in our lungs. Everybody in this room has different species of bacteria in their lungs, because as your immune system attacks these organisms, there's built-in mechanisms to their genetic code constantly making minor variations, making different proteins to fool our immune system.

This is case selection by our antibodies, and our physiology is changing those. We're changing selection of the species, perhaps ones that will survive in a higher CO_2 environment. As I sailed around the world, one of the most disturbing things was that we could barely go a mile in the ocean without seeing plastic trash. We did not anywhere, in a complete circumnavigation, see a pristine beach, a beach that wasn't covered with trash. But talk about a new environment: after the major tsunami, as we sailed across the Indian Ocean, all the beaches were covered with flip-flops, which turned into rafts for crabs. So we have a new habitat for crabs, as they float around the ocean on people's flip-flops. We are very much affecting evolution on our planet. My contention is, we need to start doing it in a deliberate fashion.

DAWKINS: I want to come back to John's point about Freeman Dyson. I didn't actually disagree with him all that much. The only thing I disagreed about with him was that he was talking about natural selection as though it were selection between species, which it is not. However, the extremely interesting point he made is the transition from a very early stage of evolution which was much more open-source, with bacteria copying and pasting information in a kind of promiscuous fashion, which is exactly what *we* are now in a position to do, using both genetic

information, through people like Craig, and also other kinds of information—cultural information.

So there is an interesting sense in which there still is a middle phase of what Dyson called the Darwinian phase, by which what he really meant was the highly ritualized phase of sexual exchange of information, which, as I say, is ritualized as opposed to the open-source system, which bacteria still do and which human biotechnology now does. By "ritualized," what I mean is that in every generation, exactly 50 percent of the genes of a male and 50 percent of the genes of a female are put together to make a new individual. Now, that is a highly stylized, ritualized, courtly kind of genetic-information exchange, which took over from the bacterial system and caused the invention of what we call a species, because a species just is a collection of individuals who are taking part in this stately gavotte of genetic exchange. Having usurped the earlier stage of promiscuity—shoving genetic information around all over the place—we're moving back into a new promiscuous phase. However, I wouldn't write off what Dyson called the Darwinian phase. It's been going for a couple of thousand million years, and it's going to go on all around us, never mind what humans are doing.

VENTER: You did use the phrase "schoolboy howler."

DAWKINS: Schoolboy howler. I did use the phrase, and that was about that one point—about suggesting that natural selection is about one species displacing another species, and that *is* a schoolboy howler. A lot of people think Darwinian selection means that one species goes extinct and another species takes over. That is not Darwinian selection; that is species extinction. It's a totally different kind of process.

BROCKMAN: Speaking for Freeman, he still maintains he's correct. One interesting aspect is that in science, debate is the way people work together, the way they advance their ideas. It's usually civil. In this case, it was very good-natured. The two major German newspapers, *Suddeutsche Zeitung* and *Frankfurter Allgemeine Zeitung*, were present, and they both ran feuilleton features on the event. And one of them said if this discussion had been in Germany, there'd be riots and fistfights. But the audiences here all seem so calm.

VENTER: Let me pick up on a point that Richard was making about the simplistic notions about Darwin and evolution. In fact, what we found in the environment was one of the biggest surprises for the scientific community. Most people expected just one dominant species. What we found were thousands, tens of thousands, of closely related organisms, all basically the same linear set of genes—tremendous variation in those genes—but there was not one dominant organism. There was this community of related organisms where perhaps none of them had gone extinct—or, if they had, there were literally thousands of ones to replace them.

The problem we've had, I think, with evolution—it has been overly simplified, because we've always been looking at the visible world, not the majority of life on this planet, which is the invisible world. In one milliliter of seawater, there are a million bacteria and 10 million viruses. In the air in this room—we've been doing the air genome project—all of you just during the course of this hour will be breathing in at least 10,000 different bacteria and maybe 100,000 viruses. I would look closely at the person sitting next to you to see what they're exhaling.

This is the world of biology we live in, that we don't see,

where evolution takes place on a minute-to-minute basis, not on the speciations of giraffes versus elephants versus kangaroos but the tens of millions of species that constantly affect the metabolism of our planet. The air we breathe comes from these organisms. The future of the planet rests in these organisms. And the question is: If we take over the design of these organisms, does that shift the balance in any way? Or is it such a small portion of what's out there that we'll only affect industrial processes, not the living planet?

DAWKINS: My vision of life is, in a sense, even more radical than that, because I would like to regard the genomes of the giraffes and kangaroos and humans that you refer to as just another set of viruses in close-knit societies. So the gene pool, I should say, of giraffes, or the gene pool of humans, or the gene pool of kangaroos is a huge society of viruses. I'm using the word loosely. I'm using the word "viruses" because the viruses you're talking about, the bacteria you're talking about, are kind of free spirits who are out there in the sea and out there in the air. But there's another whole class of them who have come together in gigantic clubs, gigantic societies, which is you and me. And so as far as a piece of DNA is concerned, there are various ways of making a living. And some of the ways of making a living are floating around free in the air and floating around free in the water. Other ways of making a living are to club together with other bits of DNA, making a genome, and influencing the phenotype, influencing the body in which they sit, to pass them on to future generations. These are just different ways of making a living. The whole of the biosphere is a gigantic collection of criss-crossing interacting DNA, some of which jumps from kangaroo to kangaroo, or from giraffe to giraffe, but via the normal route of reproduction, sexual reproduction; others of which jump around through the air or through the water. But it's all the same kind of stuff.

VENTER: In fact, the jumping, I think, is a lot farther; they can jump from planet to planet. We have organisms that can withstand 3 million rads of radiation. They can be totally desiccated. It's been shown that they can survive easily in outer space. We exchange roughly 200 kilograms of material between Earth and Mars each year. Undoubtedly, we're exchanging these organisms. It's a question of how far they can transfer. We're starting to look at the gels of space dust, to see if we can find DNA in them. These organisms, if they were shielded within a comet, within any other material, could literally last tens of millions of years, find a new source of water, and start replicating again. Our viruses can affect the universe, just not the girl next door.

DAWKINS: There's a precious beauty in the experiments you've been describing, because Charles Darwin himself did the same thing, but with transmission of organisms from continent to continent. Darwin was concerned for theoretical reasons to argue that it's possible for living things to survive long journeys in seawater or other transmission conditions. Darwin did experiments analogous to yours, in which he took seeds and showed that they could survive for long periods of time, long enough to drift across from one continent to another. It's a beautiful analogy

VENTER: I'm certain we will find bacterial life on Mars; whether it's actively replicating or not still is a question. But it won't differ from what we have on this planet.

DAWKINS: But it'll be Earth—

VENTER: Because it will either have originated there and come here, or originated here and contaminated there.

BROCKMAN: Have you thought about exoplanets?

VENTER: Dimitar Sasselov says there are 100,000 planets, just within our own galaxy, that could support life. We will find life as a universal concept. Anywhere we will find intelligent life, we will find it's a design concept. It's an electronic concept. It's an information concept. We can transfer life across the universe as digital information. Somebody else could, in their laboratories, build that genetic code and replicate it. Perhaps publishing my genome on the Internet had more implications than I thought.

BROCKMAN: When you talk about design, you're inferring that life is a technology. Would that be true?

VENTER: Life is machinery. Life is a form of technology as we learn how to engineer it and reproduce it.

BROCKMAN: One of Richard's colleagues, J. Z. Young, at Oxford, in his 1951 Reith Lecture, said we create tools and we mold ourselves through our use of them. So if life has moved from reality to a tool to a technology, how is that going to change our view of who and what we are?

VENTER: It's a question that came up at the beginning of looking at the genetic code. Many argued that we would diminish humanity by looking at our own genetic code and understanding it. That's a simplistic view. Looking at our genetic code and trying to understand how we go from the same 22,000 genes in every one of our 100 trillion cells to a John Brockman and a Richard Dawkins is far more fascinating than anybody can conjure up, I think, from any religious or poetic form. I don't think it diminishes humanity to understand it.

BROCKMAN: It sounds fascinating now. Twenty-five years from now, it'll sound, to the next generation, trite and taken for granted. Things are going to change. With this scheme of things, I don't see any place for religions. I think we're going to relate to each other differently. The whole cybernetic idea is a huge epistemological breakdown of our traditional ways of looking at each other. We go down an empirical road, until it hits a wall, and you have to rethink everything. And that's where we are right now.

VENTER: Well, it certainly changes the definition of an Internet virus. If we can have an actual virus, digitize its code, we can transmit it around the Internet and somebody else could build that same one—or, more important, a cell to make octane from carbon dioxide based on sunlight. We need to get these transfers quickly. We are a species for whom everything out of sight is out of mind. While we worry about GMOs, primarily in Europe, I worry most about the several trillion organisms that get transferred as ballast water that ships pick up in any port after they dump their cargo, and take to another part of the world, and contaminate that part of the world with all those microorganisms and viruses. This has been going on ever since ships have taken on ballast water. We are doing a cross-contamination. The ex-

periment Darwin did, every time a ship takes on ballast water, it moves someplace else and dumps that water, moving billions to trillions of organisms and viruses around to create environments that wouldn't normally exist.

BROCKMAN: The audience might be interested in your adventures with national governments in your surveying their waters in the South Pacific.

VENTER: What John's referring to—it's almost impossible, as a modern scientist today, to do what Darwin was able to do. On his voyage on a survey ship going around South America, he took biological samples, characterized them everywhere he went. We now have international treaties stipulating that every country owns every species within 200 miles of its borders. We found, as we sailed across the Pacific Ocean with a one-knot current that carried a million organisms per milliliter of ocean water across a border, they went from organisms that were international to becoming of French genetic heritage. And it changes the ownership. It changes the view of science—to the point where most states now don't want discoveries made and that information published on the Internet or in scientific journals. So we've gone to the extreme opposite of open-source, to where it's hard to find a country that doesn't want to block the publication of biological information that's either originated in that country or drifted across its borders.

BROCKMAN: At the "Life: What a Concept!" conference, you said something about artificial life—that it's not "if" but "when" it's happening, and it's going to happen sooner than we think. So, what is the prognosis on that?

VENTER: Well, just for the record, we have not yet created a cell driven by a man-made chromosome. Based on the chromosome-transplant experiment, though, we know that that is definitely possible. There's a lot of barriers to it. There's different mechanisms in cells where—because these are in fact key mechanisms of evolution—if you're a cell swimming in the ocean and you take up not a gene but a whole chromosome from another species, and it instantly transforms what you do as a species, some species wanted to develop mechanisms to protect themselves against that. There are a lot of barriers we have to overcome. I'm hopeful that will happen this year.

DAWKINS: Can I talk a bit about some of the risks? Craig, you were just talking about the sort of almost criminal contamination of oceans when tankers release ballasts of seawater and thereby contaminate one ocean with the organisms of another. And we're all now quite used to the idea of contamination of organisms. When you go to New Zealand, you hear thrushes and blackbirds, because the early settlers felt nostalgic for British birds and wanted to bring in British birds. I mean, it's criminal. The Duke of Bedford imported American grey squirrels into Britain, and now the red squirrel is all but extinct. We're entirely used to this idea of contamination. However, what's the equivalent that we might be doing now? What if scientists of the future are unable any longer to do serious molecular taxonomy work because the scientists of the twenty-first and twenty-second centuries contaminated genomes by introducing genes from other radically different parts of the living kingdoms?

It's probably all right as long as very, very careful records are kept. However, you could imagine a situation in the future where the rather strict separation—at least in Freeman Dyson's middle

stage of evolution, the sexual phase—where, on the whole, evolution is all divergent, there's virtually no cross-contamination of genes, if humans suddenly start cross-contaminating genes so you have kangaroo genes in giraffes or melon genes in aardvarks, how are we going to do our molecular taxonomy? Won't it be a bit rather like people trying to study the faunas and ecology of New Zealand?

VENTER: Richard, that's the most naïve question you've ever asked. And I assume you're asking it to be provocative, because in fact that's the opposite of what we see happens with evolution. Viruses move genes around from totally disparate species in a common fashion. We have genes in our genome that resemble some from distant viruses. In fact, a third of our genome is basically viral contaminate. When we sequenced the smallpox genome, the smallpox genome had half a dozen clearly human-derived genes. We see bacterial genes moving in a lateral fashion from *Archaea* to bacteria to plants to single-cell eukaryotes. We do have constant information exchange across the diversity of species on this planet. I've never heard the term until this meeting, that of the "schoolboy howler," but I would put this in that category, the simplistic view of biology.

DAWKINS: Are you saying, then, that a molecular taxonomist who's trying to work out, say, the taxonomy of marsupial mammals or placental mammals would be thrown because a bacterium or a virus had at some point carried a kangaroo gene into a jackal genome or something? You're not saying that. Are you?

VENTER: We're saying that we see evidence of every branch of life in almost every genome. It depends on which gene you choose, and that's been the problem with molecular taxonomy. If you choose one gene out of 2,000 or 3,000 in a genome and try and classify on that, you come up with one answer. If you pick another gene, you get a different tree. If you look at the genome as a whole, you get a totally different answer. So, yes, we see genes moving around.

You know, the visible world and these few visible species to me are somewhat bizarre extremes of evolution. They're not the standard. But if you look at those, in the marsupial versus a platypus genome you would definitely find a clear-cut similarity. If we sequenced another mammalian genome, we would not discover a single new gene. We would discover unique *combinations* that made that mammal versus us. But we have saturated the gene set for mammals. So we can say here that the gene set of mammals, over half of those are shared broadly with other species. You can't draw a bright line at every gene, and say, "These are plants and these are mammals. These are humans and these are marsupials," because we've used—it gets back to the gene-centric view—we've used those in the random design of biology, as we will use them in the very specific design we do in the laboratory. And taxonomy is something where people sort of fool themselves by justifying what they see with their visual acuity.

DAWKINS: The overlap of mammal genes that you're talking about could come about through common ancestry. So the platypus and kangaroo genomes contain shared genes because they go back to a common ancestor. That is the normal assumption made by molecular taxonomists.

VENTER: Yes, but once you have lateral transfer, whether it's due to viruses or anything else, the tree concept of life goes away.

DAWKINS: That's what I'm asking you. To what extent does molecular taxonomy now have to be, not overthrown, but at least thought of with great suspicion because you cannot tell which genes are in common because they're from a common ancestor or because they're cross-contaminated by viral or bacterial transfer?

VENTER: We can use the genetic code to watermark chromosomes. You can use it in a secret code. Basically, what we're using is the three-letter triplet code that codes for amino acids. There are twenty amino acids, and they use single letters to denote those. Using the triplet code, we can write words, sentences. We can say, "This genome was made by Richard Dawkins on (this date) in 2008." A key hallmark of man-made species, man-made chromosomes, is that they will be very much denoted that way.

You could, obviously, copy something that was out there and make minor variations and nobody would necessarily know. The other key tenet of what we're doing is, the organisms we're designing are designed *not* to survive outside of the lab. I don't know anybody who's advocating making a new species and throwing it into the ocean.

BROCKMAN: I'm sure some of you have questions.

QUESTIONER: I have a question for Richard Dawkins. You've known Craig Venter for quite a while, and you remember ten years ago, when the world was too slow for him in sequencing the genome, and he said, "I want to do it myself. I want to do it quicker." Now he announces that he wants to create artificial life to resolve the energy crisis and bring the oil price down and create new forms of energy. When will he come up with the first form of energy?

DAWKINS: You're asking me a question about Craig.

QUESTIONER: Yes. I asked him already a couple of weeks ago, and he didn't say anything about the time line. [Laughter]

VENTER: So, supposedly I told you [to Dawkins] in secret what the real answer was and you're going to reveal it now.

DAWKINS: I'm not going to reveal anything. I want an answer from Craig about the kangaroos and the— [Laughter] I think you're confusing two quite different things. Of course you can make viruses and bacteria transfer things, and we know there are a few genes that have cross-contaminated from radically different parts of the animal and plant kingdoms, but I didn't know, until you told me today—and I'm skeptical about it—that molecular taxonomy of, for example, mammals, is endangered by cross-contamination of genomes. I don't believe molecular taxonomists—yet, at least—say, "Oh, well, we can't use this gene to get our kangaroo taxonomy right, because it's clearly been imported from a rhinoceros."

VENTER: When we look at bacterial evolution, a typical bacteria will have 2,000 genes in it. Each one of those 2,000 genes has its own separate evolutionary tree, which you can construct, and none of them have the same time line that you could put together.

DAWKINS: But that's bacteria.

VENTER: But that's bacteria. So, viruses pick up bacterial genes all the time. They pick up mammalian genes all the time. A third of your genome is virus—it's not just you personally. And there

are subtle differences in those, so if a taxonomist were to measure viral genes, thinking it was a human gene, they would come up with a very different answer from one that was in the human lineage perhaps from the beginning.

QUESTIONER: You mentioned that there are 100 trillion cells in our body, so to speak. A hundred trillion. Right? Aren't most of them nonhuman? Aren't we really dependent on having a lot of animal cells in our body? And in essence are we not human but a zoo?

VENTER: No. It depends on what you had for breakfast. We have 100 trillion human cells. We have at least that many bacterial cells associated with us. So—

QUESTIONER: So we are a zoo?

VENTER: Well, it depends. There aren't too many bacterial zoos. But an important part of human metabolism is, you're not so much what you eat, as people say; you're what you feed the bacteria in your gut. When we look at the chemicals in the blood after a meal, there are roughly 2,500 compounds that we, as a species, can make. We see roughly twice that many as bacterial metabolites in our guts, from what we feed them. So we live in a bacterial milieu. We breathe it. Our guts, every orifice, our skin—we have more bacterial cells than we have human cells, and they're a key part of our existence. We can't exist in a healthy life without them. So that could be a zoo if you had a microscope.

QUESTIONER: I have two questions, actually: one referring to Richard Dawkins's latest book, *The God Delusion*. I would like to know from Venter how happy was he about this book. Because, well, if there's no God, you can't tinker with Genesis. So, you don't have any ethical problems with that, maybe. The second question is: Do you think humankind is overtaking evolution? So it will happen in the lab, and not in the natural environment anymore?

DAWKINS: The first question seemed rather a strange question. It mentioned my book *The God Delusion*, and then asked, "What's Craig Venter's attitude toward that, because . . ." And I didn't quite understand what the "because" was. Something to do with, "He doesn't have to worry about Genesis anymore." But I don't suppose he ever did worry about Genesis. [Laughter]

VENTER: I guess the assumption is, we can't play God if there *is* no God. [Laughter]

DAWKINS: All the more reason to do so.

QUESTIONER: In response to Mr. Brockman's annual *Edge* question, about where have people changed, where have the two of you changed your minds? And could you comment on Steven Pinker's response to that question, where he stated that he once thought humans were essentially not evolving anymore but now he believes they are?

DAWKINS: Right. The questioner points out that John Brockman's *Edge* website this year has a question, "What have you changed your mind about, and why?" I won't give my answer, because it takes too long to explain. However, I will say that in response to Craig Venter today, I am prepared to change my mind, if he gives a better answer to my question about molecular taxonomy. Maybe now is not the time to do it. I'm on the brink

of changing my mind, but I remain highly skeptical as to whether I will in fact have to do so.

VENTER: We'll have to go through some genome data as we follow up on this. I think Pinker thought there was no human evolution because he spent so much time at a university. [Laughter / Applause]

QUESTIONER: We've talked a lot about design and technical things. How about soul? Science tried to figure out where our souls sit. Where is it in your mind, Mr. Venter?

DAWKINS [jumps in]: The question is about where the soul sits. Either the soul doesn't exist at all—and I don't believe it does exist, in the sense of anything outside the brain—or it is a manifestation of brain activity. I certainly would think it highly, highly unlikely that there's anything like a soul that survives the death of the brain. So I think that one of the aspects of the revolution in biology is a complete destruction of dualism and of obscurantist mystification.

QUESTIONER: Craig's comment about being able to, perhaps, in the future take carbon dioxide out of the atmosphere and create fossil fuels—good ones, because we're not digging them out of the ground—is admirable. Of course, it's always dangerous to predict what future technologies will be like. But it seems to me that there are two classes of technological solutions that might be able to use your invention, when you come up with it. One would be some kind of black box that takes the carbon dioxide in the immediate vicinity of the black box and converts it into fuel. And the problem here is that you only have about 400 parts per million of carbon dioxide in the atmosphere. So you would require an enormous amount of processed energy to be able to get enough carbon dioxide to make the quantities of fuel we need.

The other broad class of technological solution would be, perhaps you could create some kind of enzyme—or whatever you would call it—but take advantage of the huge surface area of the oceans, and you could then put it into the ocean, and then it would take carbon dioxide out of the atmosphere and convert itself into oil. But then we would have the problem of the oceans being covered with oil, another undesirable solution.

VENTER: They're thoughtful questions. The first, about the concentration of CO_2, is relatively easy to deal with. The K_Ms of the enzymes and these organisms that exist throughout our planet are able to capture CO_2 out of the atmosphere, out of the water. But we don't need to rely on that. We have two phenomenal and, soon, a third point source of carbon dioxide. The two largest are power plants and cement factories. If we could simply capture back the CO_2 from those two point sources, it makes it very easy, because of the incredible concentrations you have there, and will eventually get in a cycle of a renewable source from that. We also have a third. It's a clustered carbon dioxide from a variety of sources to be pumped down into oil wells or coal beds. So, we are working in one of our programs with BP, trying to look at converting that CO_2 back into methane, so you could constantly be in a recycling mode. Once you sequester CO_2, we could use that as a source of energy instead of constantly taking more out of the ground. So we have so many incredible point sources of CO_2 production right now that that's the least of our worries.

BROCKMAN: Thank you. Thank you all for coming.

10
The Nature of Normal Human Variety

Armand Marie Leroi

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Armand Marie Leroi is a professor of evolutionary developmental biology at Imperial College London.

The question that interests me, as it does so many other people, is how to go about making a human being. It's a very difficult problem. Roughly what it boils down to is this: It's often said that the genome is something in the nature of a book. It has words, a grammar, a syntax, and of course those words have meaning. The only problem is that we don't know actually what that meaning is. So the question is, How do we decipher that? And turning that question around, looking at it from the point of view of the human body, what do those genes mean to the construction of the human body?

Of course I don't actually work on humans; they're just too inconvenient. I work on worms. This worm is *Caenorhabditis elegans*, for which Brenner, Sulston, and Horvitz won the Nobel Prize in 2002. And the reason why I and a thousand other scientists work on this worm is that, for all of its marvelous properties, it's easy to keep thousands of them in petri dishes, and it's easy to find mutants. And that's the critical thing. We find mutants that interrupt particular genes, and that tells us what those genes do and what they mean to the body of a worm.

Developmental biologists have been doing this for a long time—once a field has its Nobel, you can be sure it's reasonably