SCIENCE OF THE NOOSPHERE

Eörs Szathmáry and Terrence Deacon

With

David Sloan Wilson

Part One

David Sloan Wilson: So welcome Eörs Szathmáry and Terry Deacon. I'm so happy to be having this conversation with you about the Science of the Noosphere. That term of course was coined by Pierre Teilhard de Chardin. But it maps very importantly onto another concept, which is major evolutionary transitions. You have both had a large impact on the history of that topic. So let me begin by asking you just to introduce yourselves a little bit. You're very well known in some circles, but our audience is very, very broad. So please just introduce yourself as people and how you became scientists. Say how Teilhard entered your thoughts to the degree that he did. And then we'll swiftly get to the concept of major evolutionary transitions, which will be the unifying thread of this conversation. So Eörs, why don't you begin, and then Terry.

Eörs Szathmáry: So greetings, I'm Eörs Szathmáry, I am an evolutionary biologist, theoretical biologist, as you wish. And very early, when I became interested in the question of the origin of life, this is why chemistry is a second language to me, but then my interest became generalized as it were. And then in the mid-90s, I became very much excited by what now we call, together with the late John Maynard Smith, the major evolutionary transitions. And that means that throughout the history of life, there have been a number of steps during which complexity increased. Lower level separately reproducing entities came together to form a higher level whole. And also there has been a change in the way inheritance works, for example. So it's not only DNA that operates as a base of inheritance, but we also have language, for example, that we are using now.

And obviously before writing, that was the only way that you could transmit useful information that was complicated. So the comparative approach to all these questions keeps fascinating me, and I'm working actively on several of the transitions in between, but not all of them.

And I have not been very much influenced by Teilhard de Chardin. I think that the noosphere is an interesting idea, and probably we are going to discuss it. The omega point we might discuss as well, towards which we might be evolving. I'm very doubtful about that, but it's very important to say that Teilhard de Chardin was a Jesuit who came from the church, but he took evolution extremely seriously. And that led later, much later to very important developments also within the church, that John Paul II, you know the famous declaration where it starts, "That evolution is more than hypothesis." And I think that Teilhard de Chardin had a very important role in that change. And also currently Pope Francis has said appreciative words of Teilhard de Chardin, so things are changing. And I think that some of his ideas are rather stimulating and more timely than during the times when he wrote.

DSW: Right. That's great, Terry over to you?

Terrence Deacon: So my background is in many respects parallel, but in a different domain. I actually encountered Teilhard's work fairly early in my career, but it played almost no role until very recently. I was probably initiated in the direction of my thinking by reading the early works of many people in systems theory, cybernetic theory, and so on. But it wasn't until I encountered the philosophical and semiotic work of Charles Sanders Peirce that I sort of really got direction in my thinking. And although I had intended to pursue this in a philosophical direction, when I found myself at Harvard where I thought I would study Peirce's work, I ended up becoming much more interested in the neurosciences and did my work in terms mostly of the evolution of brains and particularly looking at the evolution of the human brain. And the link to my studies with Charles Peirce and his work had to do with language and how unusual language was.

And so I spent all through the 80s and early 90s struggling to answer the question what's unique about human brains that makes this very unusual way of communicating possible. In the process I studied even with Noam Chomsky who became in effect a strong opponent of my work and I of his. And we have ever since been that in part, because I felt that we need to look at both the biology and the underlying semiotic arguments behind language that were missing. In the mid-90s when I encountered the work that Eörs and John Maynard Smith were involved in, I also recognized while I was writing my first book, The Symbolic Species, actually, it's my second book, I should say. But when I was writing that book, it became very clear to me that the transition to language was also a major transition. And even though I was not well versed in the early 90s with that kind of thinking, it became a major driver for my thinking. As did an idea which later received a name, niche construction, that is the idea that something that an organism does external to itself actually plays a significant role in its own evolution.

A kind of, as Doug Hofstadter would call "a strange loop," so to speak. That what we do to the world, changes us. While we're in a situation very similar to that now, where language clearly has played a role, language has made technology possible. I think that ever since language evolved, we have been to some extent linked together in a way that other species are not, that is we cannot do what we do any longer without language. We cannot live without it, but language is something that's only as Eörs was hinting at just a few minutes ago, it's only transmitted collectively, it's not transmitted genetically, even though the predispositions are transmitted genetically. And that means that we are in effect more dependent on that niche, the symbolic or linguistic or cultural niche than we would probably like to think. And as a result the transition that we're beginning to face, in which communication becomes a major driver in the course of human history, is a similar sort of problem, a problem in which these capabilities are now exploding. And so it's turned my attention back to Teilhard and the idea of the noosphere.

DSW: Okay, that's awesome. Now I want to provide a timeline for this, Teilhard died in 1955. So he was actively thinking during the first half of the 20th century, mostly the 1930s and 1940s, much of his work was published posthumously. And it wasn't until the 1970s that the idea that organisms can evolve from groups as opposed to by small mutational steps from other organisms burst on the scene. I think there were some precursors to this, but it was the cell biologist Lynn Margulis who proposed that eukaryotic cells, nucleated cells, evolved not by small mutational steps from bacteria, but as symbiotic associations of bacteria, the symbiotic cell theory. So that organelles, such as mitochondria and chloroplasts actually were free living organisms in the distant past. And so the key idea here is that groups can evolve to become so cooperative that they become superorganisms, higher level organisms in their own right.

So that was the 1970s, and it wasn't until the 1990s, so very recently by my lights, that this idea was generalized by John Maynard-Smith and Eörs, in two books on the major evolutionary transitions. Bear in mind that in the 1970s, when Margulis proposed her ideas, group selection, a theory that's really needed to explain major transitions, was in its dark age. It was rejected by most evolutionary biologists at that time. And so the 1990s now is the first time that this concept became generalized and those books ended with some speculation about human language as a major transition. And then Terry's book, The Symbolic Species brings us up to 1999, if I remember correctly, Terry, and we're at the dawn of the 21st century. And now, we have this idea that goes, moving forward from, of course we have to talk about human origins and we need to talk about the whole nature of symbolic thought.

And then back to Teilhard, I mean, the whole concept of the noosphere is that mental dimension to human society. And so now at the turn of the 21st century, we're only really gaining the capacity within evolutionary science to do that. And now we're running it forward to the Internet age and then beyond to the future. And the idea that this is can be extrapolated to some kind of global cooperation or not.

And in this moment of our history, that "or not" is looming dangerously close. There's utopic outcomes, global cooperation, global brain and all that good stuff. And then there's dystopic alternatives—the collapse of civilization or sinking into some deeply global despotic society that's good for a few elites and bad for everyone else. These are possibilities that we have to consider, but in any case, there can be no more important topic than this.

And the concept of major transitions is the anchor concept basically, that somehow this is a single concept that can run everything from the origin of life to the future of the Internet age, which of course is what our series is all about.

So how to begin? I think maybe if either one of you can talk a little bit about Lynn Margulis and her symbiotic cell theory, and then I'd like to move to the very beginning of the origin of life and then kind of take the grand arc of history from the origin of life to various levels of biological organization, to humans, to cultural evolution and up, extrapolating into the future. But let's begin with Lynn Margulis, who I think is a pivotal figure, and then define the concept of major transitions in that context, the symbiotic cell theory, and then move to the origin of life. So Eörs would you like to begin, and then pass to Terry?

ES: Gladly, I appreciate the work of Lynn Margulis greatly. There is one thing though that I have to mention just for historical reasons, that's a little bit similar to what Copernicus did. I mean, also in ancient Greece, there was a heliocentric view of the world from Aristarchus. And Copernicus actually knew about that. By the same token Lynn Margulis knew that there were cell biologists in the distant past, end of the 19th century, the beginning of 20th century, for example, the Russian Mereschkowski who very clearly indicated that it's a possibility that certain of the cell organelles, little organs within a complex cell, you know we are also built of complex cells and an amoeba is a complex cell, a paramecium is a complex cell. Bacteria are very simple relative to that.

Now, so the idea that came out of this was that a bigger cell can ingest a bacterium-like creature, and have a bout of major indigestion, meaning that this bacterium that was ingested was not digested, instead, it was hanging around so to speak, in the inside of the host cell and this bacterium—and I am going to give examples what they could have been doing—this bacterium, with time, was integrated into this larger cell to such an extent that neither of the original partners can reproduce alone. This is a very important thing to actually come to a major transition where you have a point of no return, right? Now you have formed a higher level unit out of the lower level units. And the two examples that have been confirmed extremely well—and I think nowadays, everybody accepts it, partly because of the molecular and cell biological data—is that this little power plant in the cell that produces energy for our cells, called the mitochondria, once upon time, they were free living bacteria. And also the plastids, for example the green plastics that give the color to our common plants and who do the photosynthesis for the plant, they were also free living cells, cyanobacteria or blue green alga. Blue green algae, is a traditional name for them.

So for them, this coming together and living happily ever after, that was the canonical scenario that has been accepted. There were some other ideas by Lynn Margulis but also by others. Lynn Margulis was proposing that certain motility organs, cilia and flagella for the complex cells, came from bacteria, the spirochetes or the idea by, Tom Cavalier-Smith means that the so-called peroxisome which is also important for the cell, came also from an ingested bacterium, but they have not been confirmed by evidence since. But it's very important that for the plastids and the mitochondria, this is now accepted by everybody. And it's interesting that for the plastids, this kind of transition happened a number of times, repeatedly, in the sense that once you had a complex cell, that it had this plastid inside, which was turned into—the bacterium inside—was turned into a plastid.

So now this complex cell with the plastid inside was swallowed by an even bigger cell. So the photosynthetic organ of this secondary symbiosis is now the result, is coming from the primary symbiosis. So inside the big cell, you find the smaller, but still very big cell. And inside the not so big cell, you still find the descendant of the cyanobacterium doing the photosynthesis for you. And there are even tertiary symbiosis. This Russian doll, you put one doll into another, this is exactly what was happening in the case of photosynthesis. It's actually a great conundrum. I don't understand why this has never happened for respiration. I mean, for the mitochondria. It could have happened, but it didn't as far as we know. Of course, lack of evidence is not an evidence of lack, but simply the statement was that we don't know any secondary origin of the mitochondrion, let allow a tertiary one.

So the last thing I want to note here is very important. It is as David so kindly emphasized, I mean, this is a transition which cannot be understood, unlike some of them, by the idea of kin selection. I mean, there being relatedness playing a very important role because the plastids and the host cell, and the mitochondrion, in a plant cell, you have always three. I mean, those are all unrelated. So, there is no way that a mitochondrion could do the reproduction for the plastid as it were, right? Or vice versa, because one is a plastid, the other one is a mitochondria. So what you need is a group selection procedure. You are selecting basically on the boat. I mean, they are always sitting in the same boat, but the partners that came together initially had nothing to do with each other. That's an important thing. It's really what we are considering after the transition is the reproduction of the group, which can actually form progeny and you can have lineages, genealogies, and so on. And I think it's a very important thing. That is what I wanted to say.

DSW: Yeah. And the group is a community. It's selection among alternative multi-species communities, basically. And that idea seems radical. But now in the age of microbiomes, it's just like the idea of whole ecosystems being selected, including some kind of coevolution between our genes and our microbiomes. That's another story, but I think it shows you how important these ideas are. And the idea that the selection among units goes way beyond kin selection. These units that are being selected are going to be multi-species communities, large and small. They're going to be symbolic systems. They're going to be, so that's part of the generalization.

ES: Maybe just one little note, because you and even the audience might enjoy this. One of the triggers for this major transition thing was I think my 87 paper in the Journal of Theoretical Biology, and it had the title “Group Selection of Early Replicators and the Origin of Life”. And John Maynard Smith was the handling editor. And he said, "That must be right." So I think that this idea also gave rise to kind of a major transition in thinking about those things. So it goes, I think it goes back to that in our joint genealogy with John.

DSW: Yeah. And up until that point, John Maynard Smith was one of the main opponents of group selection, but this now really changed his mind at least for the case of major transitions. Terry, why don't you take it from here and segue us to the origin of life while you're at it?

TD: So what I wanted to do is to go back to the 1970s again, in the time that Lynn Margulis was writing, and one of her ideas was of course, an idea antagonistic to the idea that evolution is all a competitive process, and that she was very much more focused on cooperation among different species, among different levels. And so her approach to what she called endosymbiosis, that is symbiosis within an organism, within a cell, for example, that we've been talking about, was part of a larger view that she had of evolution that was much more cooperative, and much more involved in sort of groups interacting with each other. As a result, it was easy for her to begin to reframe many of these what we might call the complexities of cells and the complexities of bodies as cooperative relationships. Group selection of course is about the evolution of cooperative relationships, from previous components that were not previously cooperating.

There was another revolution in genetics, begins in 1970, and that's the work having to do in genetics with gene duplication. And I wanted to put these in conversation with each other, because when Japanese researcher Ohno began to recognize that maybe the evolution of larger and larger genomes was the result of genes being duplicated and possibly cooperating with each other after duplication, being eliminated, being multiplied and so on. It also changed our thinking about evolution to involve cooperation in another sense. And I'm going to sort of shift some of my conversation in this direction, because what's going on under those circumstances is that the surplus capacity that he recognized that was possible when you have gene duplication means that things can take on cooperative roles with respect to each other. And one of the things that we've learned about many gene families is that when a gene is duplicated, particularly many multiple times, it becomes possible in some cases for subfunctionalization to develop. That is for cooperation to develop within the system because of multiplication. And I thought one of the things that was very exciting, I think about the shift that John and Eörs were making was also a focus that has been brought up by a man named James Griesemer which is the idea of multiplication, that one of the things about life is that it multiplies, it makes more than it needs. And this is one of the things that makes natural selection possible, of course. Because you have more variance than you need in effect, more than needs to be passed on, selection is possible. The same thing is happening within cells, within genomes, at all kinds of levels. And multiplication, I think is a part of the story that is oftentimes underplayed. But I think that it's also a major part of this story, but in any case, this links to the situation we're talking about now, because one of the things that's happened is that all the devices that we've created, and language itself allows multiplication in the sense that there can now be many people with the same capacity, people with devices that do what we need and are kind of surplus. The result of this, however, is that differentiation of functions can evolve.

And I think one of the things that's happened in human societies is because of this capacity to share information by communication, to provide devices that aid us, to help us to do things that we couldn't have done before, also plays a role in simplifying some of the parts. And one of the things I think that's interesting about some of the more complex social organisms like eusocial insects, is that there's been a simplification, not just a differentiation, that some individuals don't do much. They do one task, and very much like what happens in human societies. And so this brings me back to the great worry about the noosphere. One of the great worries about the noosphere is a dystopian future, one in which we are much more like social insects, in which individuals lose autonomy, lose capacity, and cede it to the larger social group. So one of the interests that we have is trying to understand how evolution can persist in our own situation, and can move towards sort of a higher order group organization in which that kind of a degradation is not what occurs. I think we as individuals would find that pretty frightening.

DSW: Yeah. Let me affirm that, and reinforce it, Terry. A really hard thing to do, I think, is to recognize both the presence and absence of functional organization at any given scale. On the one hand, it is a possibility that a unit can become so cooperative that it qualifies in every sense of the word as an organism or a superorganism—or not. An alternative possibility is basically a Hobbesian war of all against all. Both exist and we need to be able to identify what's happening and of course, in any kind of policy sense to achieve cooperation. But then of course, there's different forms of cooperation and there's forms of cooperation not worth wanting, is I think one of the things that you just said. That if it removes agency from the lower level units, and we simply become like skin cells that could be shed and individuals become disposable, then that's a horrifying possibility.

So this is like threading a needle, the kind of cooperation worth wanting and expanding it to the global scale, is it there's no inevitability about it. And Teilhard did not imply that there was, although he was often taken to mean that. But this should be very suspenseful for all of us. How is it that we can achieve our global cooperation worth wanting, is what we need to achieve and see clearly and work towards it. Okay. So Terry, bring us to the origin of life. How do we take this concept, which started with the symbiotic cell theory, bacteria to nucleated cells? How does it apply to that question of questions, the origin of life?

TD: The origins of life question of course, is about how we go from chemistry, to what I like to call "normative chemistry" in which there's some good chemistry and bad chemistry. And that means you have to have a system that in effect supports itself. And there have been many, many approaches to this.

The current favorite, I think, in the community is an RNA world theory. And this was the result of the discovery, now decades past, that that RNA molecules can both function as catalysts and as information-like molecules as templates of a form. There are many alternatives and Eörs of course is very much involved in this as well.

I happen to be less attracted to the RNA world approach, in part because of my interest in the concepts of information and reference. And that's because mere replication is not about anything in some sense. And so I've been very much focused on how it is that a molecule can come to be about something else, how a molecule can come to transition to the point of being not just about other copies of itself, not just about including copies, but how a molecule can come to be the molecule that regulates the relationships between other molecules. That I think is a much more complex problem, one that I think we have not well addressed yet in the field. But as a result, there are many sort of alternatives to this. One is whether the metabolism comes first, whether information molecules come first, whether enclosure comes first. I actually favor something more general, which is that I think this sort of aboutness comes first, but that it's, again, my focus on language-like and semiotic forms of communication.

But the important point about this transition is that it's a transition into something very, very different. The second law of thermodynamics is suddenly being used against itself to produce both order and to maintain existing constraints, existing systems. So it's a transition that is a major transition, but maybe *the* major transition, in the sense that it changes the physics of the world in a sort of radical way. I think the excitement about the origins of life question is that it had to be very simple. It had to involve spontaneous processes, and yet it had to undermine one of the most basic features about the universe, the second law of thermodynamics, by finding a way in a sort of circuitous way to use the second law against itself. This makes it a really remarkable transition, a transition that I think is behind all of the transitions.

DSW: Yeah, that's incredible, and a great way to start. When you say "normative chemistry," that's so evocative because "normative" of course implies morals, which we associate with humans. And now you're associating it with basically the origin of life and semiotics and so on. So basically this takes very deep philosophical questions and puts them right in the beginning. And also we have an opportunity here in this conversation in addition to providing an overview, we have two of the deepest thinkers on this topic to discuss with each other. And of course this is very nascent science, it's not at all settled. And so we have some differences of opinion here, perhaps, that we can move on to center stage at the same time that we're providing a very broad canvas for our listeners. So Eörs over to you on the origin of life.

ES: Well, there is one thing I have to say first, that I had a very prominent mentor and he was giving lectures at what was called the Free University in Hungary. It turns out that actually it was better in a way than the university itself because at the university, all kinds of people were lecturing, at the Free University only the best ones were lecturing. And he was Tibor Ganti, originally a chemical engineer who ever since he was a secondary school student himself, he was interested in the question, "Okay, what would be the chemical foundations of life and how this could shed light on the origin of life?" So in ’71 he published a book in Hungarian which had the title, "The Principle of Life," and there he had two chemical systems linked together. One was what resembles a DNA-like molecule in which you can have what we call replication. So it's a molecule that you can extend, like this, it's like a thread and then you can basically copy, digit by digit, okay, so to speak, building block by building block, okay. That's the template replication as we call it.

And the other system that he had was a system for metabolism. But the important thing is that the metabolic system was also growing, okay? Because if you can take a template and then you copy it, then you will have exponential growth. Now he realized that you also have to do it for the metabolic system and the chemists in general, call this tendency for growth autocatalysis. Now, catalysis is something where there is a molecule and it helps the transition of another molecule X into becoming molecule Y.

Now autocatalysis is a process whereby the Y equals the catalyst itself. So what it means is that you started this one molecule of catalyst and the expense of consuming material X, you have two copies of the catalyst itself. It doesn't have to be a big molecule.

Actually, the first reaction of this, very relevant still for the origin of life, was discovered by a Russian chemist called Butlerov in the 1860-something, so quite before the Miller experiments, I have to say. It was a very simple reaction. He realized that if he takes a solution of formaldehyde, which is very simple molecule, it's one carbon atom in it and some others, two atoms of hydrogen and one atom of oxygen, that's formaldehyde. And there is also some glycolaldehyde in it, which is two formaldehyde molecules linked together. Then, sugar molecules are spontaneously appearing in the solution. And then, it was discovered that actually they are accumulating exponentially. So, what the heck is going on? That is, that this molecule of glycolaldehyde can eat up another molecule of formaldehyde, then another molecule of formaldehyde, and then it spontaneously splits into two molecules of glycolaldehyde.

So, that is real autocatalyst for you. And because it produces sugar molecules, it's also relevant for the origin of life, and it's also spontaneous. So, Ganti, in the early '70s, realized that if you want to build a biological minimal system out of qualitatively different chemical systems, then for the metabolic system, you also must have something which grows, which has its own growth. And then in '74, he realized that, "Okay, you have to put that into a bag because, otherwise, the constituents will flow away." And then, he realized that that bag also has to grow, and it has to be autocatalytic in that sense. It's actually true because, now we know for sure, I mean, ever since the Singer-Nicolson Model in '72.

The little building blocks that gives you the bag, they can spontaneously be inserted into the bag, and they can grow. And if you put all the three components together, it'll also grow in space, which means it will undergo spontaneous division. We want to see how these systems can now be realized in the lab in chemistry because that will give us a hint how this could have happened roughly 4 billion years ago in the earth. David.

DSW: Yeah. I just want to reinforce that just about every scenario requires units of selection, basically. These things must exist in numbers. There must be a population of them. Some must work better than others. There must be differential replication. There's no way to tell the story without units of selection, vesicles or so on, little protocells. And then, of course, there's many different ways that that might happen. So, maybe a little bit more from both of you on that. What were those first protocells? Were they lipid vesicles? Were they clay particles? What are some of the scenarios for these first protocells, the first units of selection?

TD: First of all, we could spend the entire session talking about the various theories. I'd rather not go too far into that. My own view is that we've been too driven by what we know about living cells, what we know about living systems. And we've ignored one thing that I think is very important, that there's an area of life that is itself on this boundary. We don't think about it as such, but it's viruses. Viruses, we think about them as just simply, these days, maybe chemical fragments of life, something is broken off. I, myself, think about the fact that viruses are only secondarily parasitic. I've spent a lot of time trying to understand what it would be like for there to be, in a sense, an autogenic self-reproducing virus. What would be the minimal possibility there?

And this has led me to go back to a number of researchers that goes all the way back to Miller and Urey, in which they were able to generate by bringing together molecules that were thought to be in a primitive planetary system, like the earth before oxygen and so on, before life, and show that you could, in fact, generate amino acids building blocks of proteins. A number of people who associated with that work recognized that there was something else that was generated in the flask during this period of time, and it was mostly in the form of a sludge, a kind of a gooey, molasses-like substance, very dark and very sticky. It turned out to be a complex of hydrogen cyanide polymers, long strings of hydrogen cyanide, basically HCN, that links together to produce a backbone that's very much like the backbone of a protein, that is carbon nitrogen backbone with side chains on it.

A group of researchers following up on this began to realize that if you take these molecules and you dissolve them in water, and they don't dissolve well because, in effect, they fold up on each other, and they're, again, like molasses and only thicker, kind of a tar. That, eventually, they break off. And the components, as a result, are amino acid-like components. So, one of the arguments is that maybe one of the original stories has to do with protein-like molecules, but maybe not proteins, something is more like a hydrogen cyanide polymer. The interesting thing about them is that they're large, and they have complex surface structure. They can play multiple roles, including roles like proteins do as catalysts.

And so, it became one of my focuses to look at this, in part, to recognize that hydrogen cyanide polymers are also very, very easily produced in the outer solar system, in areas where there's not liquid water, that they are showing up on comets in large numbers, and that in fact, they may be one of the things that rained down early on in the bombardment phase of our solar system. That maybe some of the components of life, and I think, the original component, in my own, this is a bias in this whole process. But, I think, that one can do this, instead of having a cell membrane, actually, a structure, like a virus capsule that is, in fact, holding a content, but is capable of being interrupted and broken open and so on.

So, I see viruses as a kind of after the fact model for a transition between what we would call living today, something that metabolizes and does all the things that we see even bacteria do. That is not quite life, so that we have this sort of middle range. Now, what's interesting in this, is that we have not gone back to something really, really simple.

And I think one of the real challenges for the origins of life story has to do with this simplicity problem. How can it be quite simple and do the kinds of things that are necessary to get a selection process started? And that has to do with reproduction, of course, but it also has to do with units. Something has to be a unit, and I think you bring this up as you talk about units of selection. It has to produce a sort of an individual, and that individual needs to have the ability to repair and reproduce itself.

DSW: Well, we have a lot of ground to cover, but still, I want to give Eörs a chance to have his say on the origin of life. And then, we're going to proceed to multicellularity and beyond. So, Eörs, back to you.

ES: There are several angles from which one can respond to Terry. I would like to take a rather neutral ground here and emphasize a few things. One is that, I fully agree that you possibly didn't start with what I call the holy trinity of Ganti, the compartment, the template replication, and the metabolism together. So, I introduced the term infrabiological systems about 15 to 20 years ago, where I said, "Okay. If you just make combinations of two different systems, for example, you have something like a compartment and the metabolism inside, then you already have something, which is already going very much in the direction of biology, but arguably it's not living yet." So, first thing I want to say is that, right now, in the experimental world of this branch of chemistry, what people are trying to do is exactly these infrabiological systems, combination of two that would spontaneously cooperate together and do something which is sustainable.

The second remark I wish to make is that this idea, of course, does not constrain, ab initio, so to speak, the chemical nature, the chemical rendering of the necessary coupling. So, let's not be too, too dogmatic about it. Although I believe that there was a phase when RNA was very important, but it's too complicated to begin with, if somebody's honest, immediately sees the difficulty. There must have been something, as Terry said, something which goes in the right direction, but it's significantly simpler than RNA, but it has to be able to store some chemical information. And this chemical information acquires it's meaning because it can do some function, which is useful, to the system as a whole. So, the system as a whole is a Comtean whole, as it were, because the different parts of the system get their meaning only in the light of the other systems , other subsystems. And they have to give their own conditions for existence mutually for each other.

But as I say, the chemical experimentation, the real experimentation within the theoretical domain, it's rather free. And it may not even be carbon based. I mean, that's something for the future. Chemistry is not developed enough to answer this question, conclusively. And the third one I wish to say is about the units of selection problem here. There are basically three types that you can explore. And also experimentally, it needs to be explored. One is when the molecules are on a surface. So, it's not that they are freely moving around in three dimensions. The surface already gives you a very nice population structure and there have been beautiful models of it, as you know. That's the first thing.

The second thing... I'll give you the word, but I want to finish. The second thing is where you have transient formation of groups. So, there is local interaction. You get washed away, you get mixed, and then you, again, make the local interactions. And the third one is when you are sitting in the same boat and you are reproducing. So, these are options that, probably, all of them happen by the way. That's important, I think.

TD: So, what I want to do is to actually show how this moves us forward, these discussions, because everything we talked about, this transition to what I call normative chemistry, I don't mean this term in terms of just morals, but good chemistry versus bad chemistry, helpful chemistry versus not helpful, functional chemistry versus neutral chemistry. There's no such thing outside of life that has any of those normative characters. But, notice that in everything we've said, and this doesn't matter whose theory it is, it's cooperative, that is, there needs to be components that have complementary features. And in a sense, the story from Kant is that each component is both cause and effect of the other components. That was his way of talking about it.

Now, I think that his way was maybe a little too simple. It's not just, of course, reciprocal catalysis. It's not where catalysts produce each other. It's got to be more than that. And I think one of the challenges is figuring out what's the simplest cooperation to get started. But the question that we're after is that, how you get those cooperations? How does cooperation happen spontaneously, so that, when it does occur, when a new level of group cooperation occurs, how does it stay together? How does it keep itself repaired? How does it prevent lower order processes from taking it apart, from breaking it down, and so on and so forth? The challenge has always from the origins of life been the challenge of putting things together to cooperate, so to speak, to support each other's existence, and therefore to support the existence of that whole cooperative unit when there's so many forces in the world that tend to break those things down.

DSW: That's beautiful, Terry. Thank you for saying that. Eörs? Okay. But then, I warn you. We're moving on.

ES: Yeah. I just want to add something which highlights why it is an important problem and why it is a difficult problem. So, I used to say that the problem of the origin of life is a sufficient degree of metabolite channeling without evolved enzymes. Now, let me restate this point by the following. There was a meeting when Stanley Miller was presenting his results. And then, there was another important guy in the audience, and he said, "I mean, these experiments are amazing one by one, but only one by one. Because if you put them together, nothing interesting happens." So, that's exactly the point that you have to find these different components that can synergistically help each other cooperate without destroying each other. And that, in a rudimentary system, is not trivial.

DSW: Okay. Now, we're trying to get to human origins, but we have to go by way of multicellular organisms and social insect colonies, ultrasocial insect, and other colonies. And with multicellularity, it seems simple at first because you have a single cell, let us say a nucleated cell. It begins to divide. They're genetically identical to each other, except for the odd mutation. So, what's hard to understand?

But, of course, there's so much more that needs to be understood with respect to multicellularity. Those mutations do accumulate, we call that cancer. And also, there's just the most fascinating comparison between the Internet, which we're getting to, and the nervous system, which is a system of electronic communication coordinating millions and even billions of cells.

So, I'm just dying to hear from both of you. Let's begin with multicellularity and anything that you can do to relate to why this was not a simple transition, but has its own challenges and complexity, basically maintaining cooperation, as Terry just said. The fact that the cells are genetically very similar to each other does not entirely solve the problem. And then, this idea of the nervous system as the first Internet.

ES: Thank you. This is an interesting question, David, whether it's simple or not, because some people think that it's so simple, that one of them had the title of a paper, A Minor Major Transition, and that was the origin of multicellularity. Well, it depends. So, I think, it's easier than some other transitions. And the hint is that it happened over 20 times in evolution. It happened even in bacteria. Bacteria can become also multicellular and, strangely enough, some of them have this what I call aggregational multicellularity, which means that cells are coming together. They do something. They form a fruiting body, it looks like a mushroom. And then, they reproduce, but not everybody reproduces. So, they even have a reproductive division of labor. The same kind of lifestyle also happens with complex cells with the slime molds.

That's a beautiful example of convergent evolution, starting from very different directions. But, if you look at the very complex multicelled organisms, then that happened only three times in evolution, it's plants, animals and fungi. Again, there are differences how easy it is to make. I mean, for plant-like multicellularity or mushroom-like multicellularity, it's very simple because the individual cells, they divide, they stick together and, which is important, they are not moving around relative to each other because of the cell walls stick together and that's it. So, it's a fairly rigid geometrical structure, and it's very simple. Actually, this sticking together in a rigid way is one of the reasons why cancer is not a big problem for mushrooms and plants because they cannot form metastasis.

There is local tumor growth in plants, but they cannot go move around like crazy, which happens in animals. Now, the origin of multicellularity in animals, I think, is a much more complicated question. Just look at development by itself. The development of the cnidarian, it's not that just they are dividing, and they stick together. They do all kinds of these mechanical gymnastics. I must say, it boggles the mind. No engineer would've designed it that way because it looks so complicated.

Nevertheless, it turned out to be a highly successful thing. The important thing is that it's not only the cells that can move around and crawl on top of each other and whatever, but it is very important that animals, as complete organizations, are moving around. So, I would agree with the late Lewis Wolpert, who died just last year, almost exactly a year ago, that the main and primary function of the nervous system is motor control, it's the control of movement, and everything is a secondary consequence of that. And I think, that leads seamlessly into what Terry wants to say.

DSW: Yeah, and so, on our way, we should point out that fungi, of course, with their hyphal masses, have amazing communication systems, which is sometimes electronically mediated, so hyphal growth and being coordinated and this wonderful, wonderful stuff there. And even the concept of whole forest being symbiotic associations, which might or might not be true, but I guess give the sense of possibility that there's all kinds of amazing coordination that's possible, including interspecific coordination and trust-specific coordination without nervous systems. So, Eörs, do you want to comment on that? And then, we'll pass to Terry.

ES: Actually, learning, information acquisition from experience does not necessarily require a nervous system. It needs an operational principle that is similar to parts of the nervous system, but the instantiation can be a different one. In fact, it has been proven that whatever a nervous system can do, in principle, you could do it, the same functionality, you could do with a carefully designed chemical network. But, the realization is completely different, of course.

DSW: Yep. No, that's very important. Very, very important. So, Terry, now, nevertheless, let's talk about the nervous system as the first Internet or one of the first Internets.

TD: I want to go back, first of all, to someplace that Eörs sort of mentioned, and work my way up. And that is, which I think was first synthesized, although people had various thoughts of this, a man named Leo Buss in the early 1980s. He made the argument that the three major groups that Eörs mentioned, plants, animals, and fungi, had different tricks in order to keep themselves from regressing back to autonomous cells taking over and causing trouble, and that there were three different kinds of tricks. And I think it helps us explain part of this problem. This is a kind of a ratchet effect, how to burn the bridge so you can't go back, so to speak. And for fungi, and you've been mentioning this just a few minutes ago, and that is that they have a tremendous amount of difficulty retaining communication within a cell.

So, cells have lost some autonomy, and there's a lot of information that sort of spills out collectively, so that neighboring cells are in constant communication. And to some extent, even the nuclei can move around the system. One of the problems with this, is that you don't have an easy way to differentiate tissues. It takes a very complicated system to differentiate tissues. So, when you cut into a mushroom, for example, all the tissues look a little bit different, but basically the cell types are almost identical. So, one of the problems of having complete communication like that, complete loss of individuation of the cells, is that it's difficult to differentiate. On the other hand, plants have accomplished this process of keeping the system from falling apart by sort of locking everybody in place.

And Eörs was mentioning this, that if you have a cell wall, it means that you can't determine that you're going to be the reproductive cell because wherever you are, you're stuck. And whoever's the last cell to be generated at the end of an apical meristem, they're the ones that might have a shot at passing on their genes. So that, to some extent, plants accomplish this ratchet effect by blocking the ability for any component to see ahead. Animals, it turns out, tend to block this ability by having the earliest stages of differentiation effectively controlled by the maternal source, by basically having the first few steps of differentiation not controlled by the local genome, but controlled by sort of a parent, an ancestral genome that locks everybody into a particular fate early on. Locks everybody, by this, I mean different cells.

Now, what's interesting about this is, this leads back to a philosopher named John Rawls, who argued that to build the just society, there needs to be a kind of veil of ignorance. So, you couldn't know when you come into society, whether or not you're going to be able to have lots of money, lots of influence, and so on. This is effectively biology coming up with a John Rawls' solution for multicellularity in three different ways.

Now, the reason I mention these three different ways is they’re, of course, possibilities for our own future, our own John Rawls' future, so to speak, in human biology. Having said that, I want to now sort of move towards animals. And I think, Eörs introduced this pretty well. And the real challenge is when you have cells that can move around. Now, you can use position to determine what you do and don't do. So that, as the early animal embryo develops, what happens is cells come into position with respect to each other, and their relative positions help them communicate to each other and say, "You're over here. I'm over there. You're going to become that kind of cell. I'm going to become this kind of cell." So, the three-dimensional changes in shape as an organism, as an animal develops, a multi-celled animal, uses shape position information to turn on and off genes. And as a result, it adds something else to it, a much more Darwinian-like logic for development.

That means that we have... One thing that makes, particularly animal multicellularity so interesting, is that as a result, programmed cell death plays a very significant role as well. That is, that some cells are turned themselves off because they're in a particular position where a signal comes and says, "Okay, you're not needed anymore." Now, what's remarkable and relevant in this process is that this basically says that individual cells have given up autonomy. Not only do they've given up autonomy to be reproductive cells, but they've given up autonomy sometimes even to persist for the good of the whole, so to speak. This is something pretty radical that animal bodies have produced. Well, it turns out that the animal nervous system uses this same logic, but it now uses it in sort of a doubled form, that is, the position of cells where they find themselves in the early developing embryo determines what kind of cell they're going to be.

But then, they begin to send out these long feelers, instead of just chemical communication to the neighboring cells. These long branches called axons that actually sort of probe their way through the nervous system to find a target. When they make that target, they begin to send signals. But, those signals now act like the local topographic signals we saw in a developing body. But now, they're action at a distance because a cell in one part of the nervous system can affect what a cell does in another part of the nervous system. Some of those cells also die. Some of those connections, which are overproduced, in a sense that multiplication begins. Many of them are eliminated because they're not coordinated in firing with each other. And so, we have this sort of standard statement that we tell all our students about the developing nervous system that, "Axons that fire together, wire together," which means that those that don't, that are not, in a sense, coordinated in their activity, in a sense, don't reinforce each other, another kind of group effect or cooperative effect.

DSW: Terry, another Darwinian process. So, we have basically Darwinian processes spotting other Darwinian processes. So, this is what we mean by Neural Darwinism, right?

TD: That's right. And yet, there are some really critical differences. One of them is, of course, it is not recursive. You don't develop them, cull them, develop more, cull them, develop more. It's a single-cycle Darwinian process, so to speak. And that's the same with developing multicellularity. It's also a single process. But, to end this story, and this is where Eörs and I have exactly said the same thing, nervous systems show up in motile creatures, creatures that are not rooted to the ground. We even find that animals that eventually get rooted to the ground who maybe produce mobile embryos, once they become rooted to the ground, like a sponge or various, I won't go into the long list of them, but once they do so, they oftentimes lose their nervous system, sometimes eat their nervous system, so to speak, because it's no longer necessary.

But it's not just movement that's critical because if you're going to move, you have to predict. You have to know something about what's ahead, what's behind, what's to the side. You have to have predictive organs. And so, we've also find about nervous systems is they develop typically on one end of a bilaterally symmetric creature that has a forward-moving end and a propulsive end. Those that don't have that kind of organization like jellyfish and so on, have a distributed nervous system that doesn't have a brain, so to speak.

But, if you're moving, you really need to have a leading edge. And that leading edge needs to have predictive organs like organs that sample chemicals, smell, taste, or organs that handle light frequencies, like eyes, eye spots and so on. And that means, that because the prediction is going to be mostly at one end, at the front end, you're going to have to accumulate many more cells at that predictive end of the body. And so, brains always tend to develop towards the front end, towards the part that eats, towards the part that's going forward, towards the part that's anticipating. And of course, what we see is, as organisms get more and more complex, larger and larger, that front end of the nervous system gets bigger and more differentiated in the process.

DSW: Okay. So, Eörs, go ahead. And then, I'm going to do a time check. So, Eörs, do you want to take your turn with multicellularity and animals?

ES: It's actually important to emphasize that in the nervous system, it's not always a one-shot game. I mean, for a while, it looked like that, that you are producing many neuron, many connections, you eliminate that which doesn't belong, and that's it. It turns out to be not the case. There is this very interesting phenomenon, which is called structural plasticity. Structural plasticity means that it's not only the old fashioned, heavy, synaptic plasticity where a synapse, which already exists, can become weaker or stronger. But, actually, there are new connections that are physically made in real time in animals. And you can even watch them now with sophisticated microscopes. So, new connections are being made, and old connections are being eliminated. So, actually, it's recursive in that sense, and it can have many rounds of production, of variation and selection. And I think, this is a very important process, and we are not fully aware, I believe, of all the algorithmic consequences of that. That's one point that I wanted to make, but I think it's very important.

The second thing is that there are other examples where evolution by natural selection has reinvented itself, so to speak, and that's the working of the adaptive immune system, in our branch of animals actually evolved twice, but actually discovered very much the same principles, which means that you are actually producing a lot of variation because you have elevated mutation rates, and you have got what is called somatic recombination. And this is how you can generate antibody diversity. And then, you are doing the selection on this emerging population those antibodies that are binding to the antigen very efficiently are going to be selected. And now it happens painfully for us with COVID, you can watch it in real time again. But it's very important that it has been discovered by evolution itself, how to harness an evolutionary system within itself. I think it's remarkable.

DSW: Yeah. So this is the idea that that Darwinian evolution can be intragenerational in addition to intergenerational, and without getting into the neural mechanisms, much can be said about our behavioral system as like the immune system with both an adaptive and innate component. So we have lots of psychological mechanisms, evolutionary psychologists like to talk about that evolve by genetic evolution, they get triggered by environmental circumstances, don't change during the course of our lifetimes. And then there's the open-ended part of our behavioral systems, what B.F. Skinner called "selection by consequences," which is basically like the the adaptive component of the immune system. And of course it has a mechanistic basis, but even without that basis, we can make the observation that the individual human and many other species have this ability, basically selection by consequences. They behave every which way, and those that are rewarded in various ways, then they are notched up in frequency. That's the matching law, so to speak even before we know what the mechanistic basis is.

DSW: Okay. So onto our next chapter from multicellular organisms to societies of organisms that become so cooperative that they qualify as superorganisms. And the famous examples are the eusocial insects, the ants, the bees, the wasps, the termites, which were called superorganisms way back when people like Wheeler in the early 20th century said, "These are superorganisms." They have their own complicated history, but I think nowadays I think they fall very naturally into the concept of major evolutionary transitions. And they're so interesting because the members of these societies are obviously not physically connected and nevertheless, by virtue of the ways that they cooperate, often through chemical signals, pheromones and all that, or of course auditory, all the modalities. They truly do qualify as superorganisms complete with group minds. And there's the most wonderful work by people like Tom Seeley, Honeybee Democracy, as to how there is definitely a cognitive dimension, a mental dimension to non-human ultra cooperative societies. So we have whole episodes on this in the series, but so eager to hear what you have to say about this major transition, nonhuman societies that are ultra cooperative. Who'd like to begin?

ES: Obviously social insects have been around and mankind always saw them. And they were fascinated and they were puzzled by their existence. One of the striking things was that in the highly evolved social insects, not everybody is reproducing. And that was a conundrum. Darwin was puzzled by that, but since he was very smart, he figured out that maybe the real unit here that we have to focus on is not the individual, but the family, right, without we could say it's a kin group, right? And if now different families are competing with each other, that it might very well be the case that certain individuals by sacrificing themselves in terms of reproductive success would actually have the others to reproduce, it might actually pay off because of the synergistic benefits that this reproductive division of labor is giving.

So that's the first thing that we have to be startled by. The second thing is that something which is important for the organisms, which we called epigenetic inheritance plays also a very important role in those societies. We didn't explicitly mention it when we talked about differentiation in conventional organisms, that it's not only the DNA, the genetic material that is being passed on from cell to cell. You know, for example, if a liver cell divides it gives rise to two liver cells. But you know, the liver cell developed during the development, there was no liver cell. There was only a zygote. So the lineage of cells that went in the direction of being a liver cell acquired during the developmental state, the state of being a liver cell. But apparently when it divides, it's also not only the genetic material, but this state of being a liver cell is also being passed on.

And it turns out to be the case that what is very important is that certain genes are on, which means that they are active. Other genes are off. This is how you can make cells that look different and work differently. But once you are able to pass this information on, okay, keep this gene on, keep this gene off. So once you can also transmit the switches, then you solve a problem that is called epigenetic, but it's also a form of inheritance. Now, this type of inheritance is also important for social insects, because whether you are becoming a queen or a worker that depends on your diet, right? And that diet induces a certain epigenetic change, meaning you are either going this way or that way, just like the determination of cell fate, you either go this way or that way. And that can also so be induced by other cells in the neighboring tissue, for example. So that's the second important thing that we have to face.

And the third one is that it's not only the reproductive division of labor that is important, but you actually have different kinds of workers. For example, if you look at a beautiful illustration, for example, in the old book by …. on the animal world, you see these beautiful graphics that look into the inside of a termite mound. And in the middle there is a big sausage. Now that sausage is the only reproductive individual. And there are all kinds of different animals. They look as if they were coming from different species. Yes, but they are members of not only of the same species, but of the same colony. But you know, there is a soldier which looks completely different from another guy who does a certain type of work.

So it's not only the reproductive division of labor, but also this division of labor of the household that is very active. And all together, the whole unit works very much like an integrated human city because they have to solve everything. They have to get rid of the dead for example, you cannot accumulate the dead because then you will be choked and you will get infections and so on. So some people call it the wisdom of the hive, in parallel with the wisdom of the body. And this is what exactly what has happened in evolution, the hive got its wisdom at the level which is above the individual through evolution.

DSW: Yeah, exactly, Eörs, and just to build upon that a little bit, the unit is not necessarily the family, there's so many social insect colonies in which the relatedness is actually not that high. There's multiple queens, there's multiple patrilines and so on and so forth. And actually the unit is a multi-species community, because if you look at the termites and if you look at the leaf cutter ants and other societies, there's all these symbionts that are in there. And so it comes down, and this is a general statement that we could make about major evolutionary transition, these units of selection, they can be a single species. They can be a multi species, their members can be very highly related or not so much. There obviously has to be variation among units. I mean, there has to be that much variation, but there's so much diversity in what constitutes a unit of selection.

And that's one reason why kin selection is incomplete basically because it notes this one variable—genetic relatedness—among the members. But, and of course that has an impact, but is not the one and only thing. So I think that's why the ultra social species slots so nicely into the major evolutionary transitions framework basically. That's the way it originated, and they've been called superorganisms since antiquity. Let's continue to call them superorganisms. So anyhow, just wanted to put that in there. And so Terry, do you want to continue this a wonderful conversation?

TD: Yeah. So a couple of things that I wanted to focus on because we've covered I think the overarching picture. What I'm interested in is two things. First of all, why it's different than a multicelled organism. Obviously social groups are not bounded, not physically bounded. They're individuals, their components are able to move. That's a critical feature. The second thing is that like when we talked about multicellularity of plants, fungi, and animals, there is a ratchet like effect. You can't go back, in multicellularity when there's an error made in turning genes off and turning genes on, you have a problem, it's called cancer. Cells that previously were dividing uncontrollably, building a large organism, at some point have to slow down or stop. So for example, for most neurons when they reach what we call terminal differentiation, they'll never divide again. Muscle cells, they reach terminal differentiation, they don't divide again, unless there's an error, unless the genes that are involved in replication come on again.

So one of the things that has to happen in building multicellularity is you to have these ratchet effects, something that keeps the system from going back. In the case of social groups or social insects, one of the things that you have to do is to ensure that the components not only maintain their function, but also don't recover some degree of autonomy. So one of the things that happens in the eusocial insects whether, whether we're dealing with those that are closely related, like in bees and ants or in fact can sometimes be combinations like in termites and so on, and with a very different kind of inheritance system, what has to happen is something that keeps the system from regressing, keeps components that were differentiated to be, say, a worker or a soldier or whatever from actually recovering or to keep workers from becoming queens.

One of the things that happens, and this is very much like the differentiation that you mentioned before, is that what happens is that hormones or pheromones of various kinds are used to create body types, to restructure the body, to restructure the nervous system in such a way that it cannot do the other things that basically shuts off some of these opportunities. Now, the question that I'm most interested in when we talk about both multicellularity, but in particular, also social, eusocial-like relationships. And I think this will also apply when we begin talking about human beings, is that one of things that has to happen in order to give up autonomy, in order to move from autonomous life to non-autonomous life in which you're collectively working as a group, there have to be sort of benefits to giving this up. And in fact, there has to be a certain point that you become, I like to describe this as a kind of addiction.

Addiction takes place when there's been enough of a change in the system so that giving up this dependence on something external to yourself is now too painful, too difficult. You can't go back with respect to opiates, the nervous system has changed so radically by the infusion of opiates, that to give it up becomes painful. A whole bunch of systems react negatively, in effect you've become stuck. You can't get out of the system. This is a ratchet like effect. I think one of the challenges in explaining the origins of eusociality, but also the origins of multicellularity. And eventually I would make the claim the origins of human sociality and language in particular is that there has to be kind of an addiction process that takes place. That is one of the things that has to happen is that in order to give up the tendency to become autonomous, to give of up the tendency to sort of break away, there has to be big costs.

And once there is an advantage to being in a group, it now becomes possible to give up some autonomy and still do well. But once you've given up some of these capacities to go back, you're now addicted and stuck. I think that's an important part of the transition to eusociality that we've not been paying a lot of attention to.

How is it that the component organisms in a social group have gained enough support by being social, by being collective? That in a sense they are... and I'll anthropomorphize it by saying they're willing to give up the possibility of becoming autonomous again. I think that one of the reasons that this happens is because the longer you are dependent, the more likely the autonomous capabilities are going to degrade. I think that's the same for addiction to opium, but I also suspect it plays a role in these other kinds of processes that addict us so to speak, to be components in a larger social group.

My suspicion is for humans that this has two parallels. One is our addiction to the social group for our language. We can't have a language if we're not in a social group, we're addicted to a linguistic unit. And that also addicts us to the culture that goes along with it. But in addition to this, with our current situation, we're becoming addicted to our technologies, addicted to our communication systems. We can't do any longer without the devices that we're talking on, whether they're cell phones or Internet and so on, it's given us incredible capabilities, but we now really can't go back easily without tremendous costs.

DSW: You use, Terry, a wonderful example that I'll bring up of vitamin C dependence, basically that many species could manufacture their own vitamin C. But in some species, their environment has abundant vitamin C. And so any mutation that knocks out the ability to synthesize it doesn't matter. And so these organisms then lose the ability to manufacture it themselves, it's of no consequence, because it's available in the environment, but then they become addicted as you say, they can no longer live in environments without vitamin C. So that's a really nice example. And what you're saying here is that this is what takes place in major transitions. You become a member of a group, that group becomes very cooperative. Other members are doing things that you used to have to do by yourself. Now you don't need to anymore, that degrades, and now you're addicted. I think of course the addiction here is a very good addiction. One problem with that word of course, is that it has such negative connotations, but this is a positive addiction. But apart from that, I think it's a very important concept that you've developed. And I think it's a very important part of all major evolutionary transitions.

ES: Well, I want to come back to something that we just started, and that is the origin of the eukaryotic cell, right? As we said, the mitochondria, these little power plants once upon a time were free living bacteria. Now, if you look at mitochondria today, you see that the vast majority of the original genes that they had in them were lost. And a fraction now of those genes are in the nucleus, the nucleus of the whole cell. So this has several consequences. One of them is that the mitochondrion cannot escape from the cell now, it's impossible because you would leave the genes that help you to function. Some of the genes, most of genes are actually outside of you. So you cannot just grab them. They don't have a hand to do this operation, so they cannot get out. And the second thing is that they also cannot have cancer. There is no mitochondrial cancer because the reproduction of the mitochondria is now controlled by the nucleus which gives us this idea—that I introduced with John—the phenomenon of contingent irreversibility, which means that things are not logically impossible to reverse, but you would have so many reverse steps to do, that for all practical purposes, it's impossible to do. That's contingent irreversibility, which entrenches many of these transitions.

DSW: Yeah. I think it's important to add though, that even after you become addicted, then it's still possible for mutations to occur that are regarded as parasitic. You haven't left the cell, but you're still not contributing to the cooperation. You still might be disruptive coordination. You still might be cancerous. So this addiction concept while very important does not solve those particular problems. So I think that's important to get out there as well.

TD: So I was going to say, just in addition to that, the story is not just the mitochondria, not only have they lost over 90%, and this is true of their genome, but as have chloroplasts, that also the nuclear cell, the cell that they have maybe been incorporated into is also now dependent on mitochondria. It's lost its ability to do energy production. So in a sense, it's co-addiction, or maybe co-dependency that we're really talking about, and this notion of endosymbiosis and whether it's our own endosymbionts are, or the endosymbionts in various insects allow them to, for example, to digest cellulose and so on. Basically each becomes degraded with respect to the other, because of their cooperation. And just to sort of shift back to where we began, there is now since the nineties, since the time that Eörs and others began talking about these transitions and this kind of a contingent irreversibility issue, it's now become a major part of discussing molecular evolution within the cell. How it is that for example, the spliceosome evolved and so on. There is a kind of similar argument, it's sometimes been called contingent neutral evolution, or DDC, duplication, degeneration and complementation.

The interesting thing is that DDC parallels Darwin in an interesting way. In a slightly different way. D-duplication is multiplication is reproduction. Degeneration is variation. Complementation is in a sense what adaptation is, fitting. DDC is a variant at the molecular level, at the social level, that's a variant of the Darwinian model, but it's not quite the same. And the reason it's not the same is that complementation occurs within a unit, competition occurs between units. But the same logic is there all the way up and down. And that means that that logic is probably also relevant to the logic that we're going to be talking about when it comes to human beings.

DSW: Wow. So basically it's taken us two hours to get to this point, and then we have the whole phenomenon of human, the human phenomenon, which is the correct translation of Teilhard's book to go in a second session. So gentlemen it has been so wonderful, what a ride, and I look forward to Part Two of this, which itself is part of our series on the Science of the Noosphere.