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The THIRD CULTURE

by John Brockman

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LYNN MARGULIS: At any fine museum of natural history—say, in New York, Cleveland, or Paris—the visitor will find a hall of ancient life, a display of evolution that begins with the trilobite fossils and passes by giant nautiloids, dinosaurs, cave bears, and other extinct animals fascinating to children. Evolutionists have been preoccupied with the history of animal life in the last five hundred million years. But we now know that life itself evolved much earlier than that. The fossil record begins nearly four thousand million years ago! Until the 1960s, scientists ignored fossil evidence for the evolution of life, because it was uninterpretable.

I work in evolutionary biology, but with cells and microorganisms. Richard Dawkins, John Maynard Smith, George Williams, Richard Lewontin, Niles Eldredge, and Stephen Jay Gould all come out of the zoological tradition, which suggests to me that, in the words of our colleague Simon Robson, they deal with a data set some three billion years out of date. Eldredge and Gould and their many colleagues tend to codify an incredible ignorance of where the real action is in evolution, as they limit the domain of interest to animals—including, of course, people. All very interesting, but animals are very tardy on the evolutionary scene, and they give us little real insight into the major sources of evolution's creativity. It's as if you wrote a four-volume tome supposedly on world history but beginning in the year 1800 at Fort Dearborn and the founding of Chicago. You might be entirely correct about the nineteenth-century transformation of Fort Dearborn into a thriving lakeside metropolis, but it would hardly be world history.

By "codifying ignorance" I refer in part to the fact that they miss four out of the five kingdoms of life. Animals are only one of these kingdoms. They miss bacteria, protoctista, fungi, and plants. They take a small and interesting chapter in the book of evolution and extrapolate it into the entire encyclopedia of life. Skewed and limited in their perspective, they are not wrong so much as grossly uninformed.

Of what are they ignorant? Chemistry, primarily, because the language of evolutionary biology is the language of chemistry, and most of them ignore chemistry. I don't want to lump them all together, because, first of all, Gould and Eldredge have found out very clearly that gradual evolutionary changes through time, expected by Darwin to be documented in the fossil record, are not the way it happened. Fossil morphologies persist for long periods of time, and after stasis, discontinuities are observed. I don't think these observations are even debatable. John Maynard Smith, an engineer by training, knows much of his biology secondhand. He seldom deals with live organisms. He computes and he reads. I suspect that it's very hard for him to have insight into any group of organisms when he does not deal with them directly. Biologists, especially, need direct sensory communication with the live beings they study and about which they write.

Reconstructing evolutionary history through fossils—paleontology—is a valid approach, in my opinion, but paleontologists must work simultaneously with modern-counterpart organisms and with "neontologists"—that is, biologists. Gould, Eldredge, and Lewontin have made very valuable contributions. But the Dawkins-Williams-Maynard Smith tradition emerges from a history that I doubt they see in its Anglophone social context. Darwin claimed that populations of organisms change gradually through time as their members are weeded out, which is his basic idea of evolution through natural selection. Mendel, who developed the rules for genetic traits passing from one generation to another, made it very clear that while those traits reassort, they don't change over time. A white flower mated to a red flower has pink offspring, and if that pink flower is crossed with another pink flower the offspring that result are just as red or just as white or just as pink as the original parent or grandparent. Species of organisms, Mendel insisted, don't change through time. The mixture or blending that produced the pink is superficial. The genes are simply shuffled around to come out in different combinations, but those same combinations generate exactly the same types. Mendel's observations are incontrovertible.

So J.B.S. Haldane, without a doubt a brilliant person, and R.A. Fisher, a mathematician, generated an entire school of English-speaking evolutionists, as they developed the neo-Darwinist population-genetic analysis to reconcile two unreconcilable views: Darwin's evolutionary view with Mendel's pragmatic, anti-evolutionary concept. They invented a language of population genetics in the 1920s to 1950s called neo-Darwinism, to rationalize these two fields. They mathematized their work and began to believe in it, spreading the word widely in Great Britain, the United States, and beyond. France and other countries resisted neo-Darwinism, but some Japanese and other investigators joined in the "explanation" activity.

Both Dawkins and Lewontin, who consider themselves far apart from each other in many respects, belong to this tradition. Lewontin visited an economics class at the University of Massachusetts a few years ago to talk to the students. In a kind of neo-Darwinian jockeying, he said that evolutionary changes are due to the Fisher-Haldane mechanisms: mutation, emigration, immigration, and the like. At the end of the hour, he said that none of the consequences of the details of his analysis had been shown empirically. His elaborate cost-benefit mathematical treatment was devoid of chemistry and biology. I asked him why, if none of it could be shown experimentally or in the field, he was so wedded to presenting a cost-benefit explanation derived from phony human social-economic "theory." Why, when he himself was pointing to serious flaws related to the fundamental assumptions, did he want to teach this nonsense? His response was that there were two reasons: the first was "P.E." "P.E.?," I asked. "What is P.E.? Population explosion? Punctuated equilibrium? Physical education?" "No," he replied, "P.E. is 'physics envy,'" which is a syndrome in which scientists in other disciplines yearn for the mathematically explicit models of physics. His second reason was even more insidious: if he didn't couch his studies in the neo-Darwinist thought style (archaic and totally inappropriate language, in my opinion), he wouldn't be able to obtain grant money that was set up to support this kind of work.

The neo-Darwinist population-genetics tradition is reminiscent of phrenology, I think, and is a kind of science that can expect exactly

the same fate. It will look ridiculous in retrospect, because it is ridiculous. I've always felt that way, even as a more-than-adequate student of population genetics with a superb teacher—James F. Crow, at the University of Wisconsin, Madison. At the very end of the semester, the last week was spent on discussing the actual observational and experimental studies related to the models, but none of the outcomes of the experiments matched the theory.

I've been critical of mathematical neo-Darwinism for years; it never made much sense to me. We were all told that random mutations—most of which are known to be deleterious—are the main cause of evolutionary change. I remember waking up one day with an epiphanous revelation: I am not a neo-Darwinist! It recalled an earlier experience, when I realized that I wasn't a humanistic Jew.

Although I greatly admire Darwin's contributions and agree with most of his theoretical analysis and I am a *Darwinist*, I am not a *neo-Darwinist*. One of Darwin's major insights is the recognition that all organisms are related by common ancestry. Today direct evidence for common ancestry—genetic, chemical, and otherwise—is overwhelming. Populations of organisms grow and reproduce at rates that are not sustainable in the real world, and therefore many more die or fail to reproduce than actually complete their life histories. The fact that all the organisms that are born or hatched or budded off do not and cannot possibly survive *is* natural selection. Observable inherited variation appears in all organisms that are hatched, born, budded off, or produced by division, and some variants do outgrow and outreproduce others. These are the tenets of Darwinian evolution and natural selection. All thinking scientists are in complete agreement with these basic ideas, since they're supported by vast amounts of evidence.

Neo-Darwinism is an attempt to reconcile Mendelian genetics, which says that organisms do not change with time, with Darwinism, which claims they do. It's a rationalization that fuses two somewhat flawed traditions in a mathematical way, and that is the beginning of the end. Neo-Darwinist formality uses an arithmetic and an algebra that is inappropriate for biology. The language of life is not ordinary arithmetic and algebra; the language of life is chemistry. The practicing neo-Darwinists lack relevant knowledge in, for example, microbiology, cell biology, biochemistry, molecular biology, and cytoplasmic genetics. They avoid biochemical cytology and microbial ecology. This is comparable to attempting a critical analysis of Shakespeare's Elizabethan phraseology and idiomatic expression in Chinese, while ignoring the relevance of the English language!

The neo-Darwinists say that variation originates from random mutation, defining mutation as any genetic change. By randomness they mean that characters appear randomly in offspring with respect to selection: if an animal needs a tail, it doesn't develop this tail because it needs it; rather, the animal randomly develops all sorts of changes and those with tails survive to produce more offspring. H.J. Muller, in the 1920s, discovered that not only do X rays increase the fruit-fly mutation rate, but even if fruit flies are isolated completely from X rays, solar radiation, and other environmental perturbation, a spontaneous mutation rate can be measured. Inherited variants do appear spontaneously; they have nothing to do with whether or not they're good for the organism in which they appear. Mutation was then touted as the source of variation—that upon which natural selection acted—and the neo-Darwinian theory was declared complete. The science remaining required filling in the gaps in a "theory" with very few holes.

From many experiments, it is known that if mutagens like X rays or certain chemicals are presented to fruit flies, sick and dead flies result. No new species of fly appears—that is the real rub. Everyone agrees that such mutagens produce inherited variation. Everyone agrees that natural selection acts on this variation. The question is, From where comes the useful variation upon which selection acts? This problem has not yet been solved. But I claim that most significant inherited variation comes from mergers—from what the Russians, especially Konstantin S. Mereschkovsky, called *symbiogenesis* and the American Ivan Emanuel Wallin called *symbionticism*. Wallin meant by the term the incorporation of microbial genetic systems into progenitors of animal or plant cells. The new genetic system—a merger between microbe and animal cell or microbe and plant cell—is really different from the ancestral cell that lacks the microbe. Analogous to improvements in computer technology, instead of starting from scratch to make all new modules again, the symbiosis idea is an interfacing of preexisting modules. Mergers result in the emergence of new and more complex beings. I doubt new species form just from random mutation.

Symbiosis is a physical association between organisms, the living together of organisms of different species in the same place at the same time. My work in symbiosis comes out of cytoplasmic genetic systems. We were all taught that the genes were in the nucleus and that the nucleus is the central control of the cell. Early in my study of genetics, I became aware that other genetic systems with different inheritance patterns exist. From the beginning, I was curious about these unruly genes that weren't in the nucleus. The most famous of them was a cytoplasmic gene called "killer," which, in the protist *Paramecium aurelia*, followed certain rules of inheritance. The killer gene, after twenty years of intense work and shifting paradigmatic ideas, turns out to be in a virus inside a symbiotic bacterium. Nearly all extranuclear genes are derived from bacteria or other sorts of microbes. In the search for what genes outside the nucleus really are, I became more and more aware that they're cohabiting entities, live beings. Live small cells reside inside the larger cells. Understanding that led me and others to study modern symbioses.

Symbiosis has nothing to do with cost or benefit. The benefit/cost people have perverted the science with invidious economic analogies. The contention is not over modern symbioses, simply the living together of unlike organisms, but over whether "symbiogenesis"—long-term symbioses that lead to new forms of life—has occurred and is still occurring. The importance of symbiogenesis as a major source of evolutionary change is what is debated. I contend that symbiogenesis is the result of long-term living together—staying together, especially involving microbes—and that it's the major evolutionary innovator in all lineages of larger nonbacterial organisms.

In 1966, I wrote a paper on symbiogenesis called "The Origin of Mitosing [Eukaryotic] Cells," dealing with the origin of all cells except bacteria. (The origin of bacterial cells is the origin of life itself.) The paper was rejected by about fifteen scientific journals, because it was flawed; also, it was too new and nobody could evaluate it. Finally, James F. Danielli, the editor of *The Journal of Theoretical Biology*, accepted it and encouraged me. At the time, I was an absolute nobody, and, what was unheard of, this paper received eight hundred reprint requests. Later, at Boston University, it won an award for the year's best faculty publication. I was only an instructor at the time, so my Biology Department colleagues reacted to the commotion and threw a party. But it was more of "Isn't this cute," or "It's so abstruse that I don't understand it, but others think it worthy of attention." Even today most scientists still don't take symbiosis seriously as an evolutionary mechanism. If they were to take symbiogenesis seriously, they'd have to change their behavior. The only way behavior changes in science is that certain people die and differently behaving people take their places.

Next, expanding the journal article, after ten years of research and six weeks of intense writing, I produced a book called *The Origin of Eukaryotic Cells*. Even under contract, it was rejected by Academic Press. Finally, in 1970, the revised and improved work was published by Yale University Press. Now called *Symbiosis in Cell Evolution*, the most recent version of the statement is in a second—really a third—edition. Published by W.H. Freeman in 1993, that book is my life's work. It details the role of symbiosis in the evolution of cells, which leads directly to the origin of mitotic cell division and meiotic sexuality. My major thrust is how different bacteria form consortia that, under ecological pressures, associate and undergo metabolic and genetic change such that their tightly integrated communities result in individuality at a more complex level of organization. The case in point is the origin of nucleated (protoctist, animal, fungal, and plant) cells from bacteria.

While Gould and the others tend to believe that species only diverge from one another, I claim that—more important in generation of variation—species form new composite entities by fusion and merger. Symbiogenesis is an extremely important mechanism of evolution. Symbiogenesis analysis impacts on developmental biology, on taxonomy and systematics, and on cell biology; it hits some thirty subfields of biology, and even geology. Symbiogenesis has many implications, which is part of the reason it is controversial. Most people don't like to hear that what they have been doing all these years is barking up the wrong tree.

My argument is radical only to the extent that it inspires scientists to change their status quo about many issues. To take seriously our *Five Kingdoms* concept (the book by Karlene V. Schwartz and me is based on work by Robert H. Whittaker and Herbert F. Copeland) a school or a publisher would have to change its catalog. A supplier has to relabel all its drawers and cabinets. Departments must reorganize their budget items, and NASA, the National Science

Foundation, and various museums have to change staff titles and program-planning committees. The change from "plants versus animals" to the five kingdoms (bacteria, protoctista, animals, fungi, and plants) has such a profound implication for every aspect of biology as a social activity that resistance to accept it abounds. Scientists and those who pay them have to dismiss or ignore this potential reorganization because accepting the shifting boundaries and new alliances is strange and costly. It is far easier to stay with obsolete intellectual categories.

For more than a billion years, the only life on this planet consisted of bacterial cells, which, lacking nuclei, are called prokaryotes, or prokaryotic cells. They looked very much alike, and from the human-centered vantage point seem boring. However, bacteria are the source of reproduction, photosynthesis, movement—indeed, all interesting features of life except perhaps speech! They're still with us in large diversity and numbers. They still rule Earth. At some point, a new more complex kind of cell appeared on the scene, the eukaryotic cell, of which plant and animal bodies are composed. These cells contain certain organelles, including nuclei. Eukaryotic cells with an individuated nucleus are the building blocks of all familiar large forms of life. How did that evolution revolution occur? How did the eukaryotic cell appear? Probably it was an invasion of predators, at the outset. It may have started when one sort of squirming bacterium invaded another—seeking food, of course. But certain invasions evolved into truces; associations once ferocious became benign. When swimming bacterial would-be invaders took up residence inside their sluggish hosts, this joining of forces created a new whole that was, in effect, far greater than the sum of its parts: faster swimmers capable of moving large numbers of genes evolved. Some of these newcomers were uniquely competent in the evolutionary struggle. Further bacterial associations were added on, as the modern cell evolved.

One kind of evidence in favor of symbiogenesis in cell origins is mitochondria, the organelles inside most eukaryotic cells, which have their own separate DNA. In addition to the nuclear DNA, which is the human genome, each of us also has mitochondrial DNA. Our mitochondria, a completely different lineage, are inherited only from our mothers. None of our mitochondrial DNA comes from our fathers. Thus, in every fungus, animal, or plant (and in most protoctists), at least two distinct genealogies exist side by side. That, in itself, is a clue that at some point these organelles were distinct microorganisms that joined forces.

David Luck and John Hall, research geneticists at Rockefeller University, recently made an astounding discovery that I more or less predicted twenty-five years ago. They demonstrated by well-developed techniques something they were not even seeking: a peculiar DNA—outside the nucleus of the cell, outside the chloroplast, and outside the mitochondria. This extranuclear DNA, these genes outside the nucleus, can be interpreted as remnants of ancient, invasive, squirming bacteria whose aggressive association presaged the merger.

If their discovery is correct—and at least three teams of researchers have disputed it—then the nonnuclear genetic system Hall and Luck revealed in green algae may represent the stripped-down remnants of bacteria inside all of us. The growth, reproduction, and communication of these moving, alliance-forming bacteria become isomorphic with our thought, with our happiness, our sensitivities and stimulations. If mine is a correct view, it organizes a great deal of knowledge. There are unambiguous ways of testing the main points: The implication is that we are literally inhabited by highly motile remnants of an ancient bacterial type that have become, in every sense, a part of ourselves. These thriving partial beings represent the physical basis of *anima*: soul, life, locomotion; an advocation of materialism in the crassest sense of the word. Put it this way: a purified chemical is prepared from brain and added to another purified chemical. These two chemicals—two different kinds of motile proteins—together crawl away, they locomote. They move all by themselves. Biochemists and cell biologists can show us the minimal common denominator of movement, locomotion. *Anima*. Soul. These moving proteins I interpret as the remains of the swimming bacteria incorporated by beings who became our ancestors as they became us.

The minimal-movement system is so physically and chemically characterizable that complete consensus exists that "motility proteins" are composed of typical carbon-hydrogen bonds, and so forth. All the details are agreed upon by cell biologists and biochemists. But I think an understanding of the extent to which the evolutionary origin involved symbiogenesis must be acknowledged. Such acknowledgment will lead to new awareness of the physical basis of thought. Thought and behavior in people are rendered far less mysterious when we realize that choice and sensitivity are already exquisitely developed in the microbial cells that became our ancestors. Even philosophers will be inspired to learn about motility proteins. Scientists and nonscientists will be motivated to learn enough chemistry, microbiology, evolutionary biology, and paleontology to understand the relevance of these fields to the deep questions they pose.

My primary work has always been in cell evolution, yet for a long time I've been associated with James Lovelock and his Gaia hypothesis. In the early seventies, I was trying to align bacteria by their metabolic pathways. I noticed that all kinds of bacteria produced gases. Oxygen, hydrogen sulfide, carbon dioxide, nitrogen, ammonia—more than thirty different gases are given off by the bacteria whose evolutionary history I was keen to reconstruct. Why did every scientist I asked believe that atmospheric oxygen was a biological product but the other atmospheric gases—nitrogen, methane, sulfur, and so on—were not? "Go talk to Lovelock," at least four different scientists suggested. Lovelock believed that the gases in the atmosphere were biological. He had, by this time, a very good idea of which live organisms were probably "breathing out" the gases in question. These gases were far too abundant in the atmosphere to be formed by chemical and physical processes alone. He argued that the atmosphere was a physiological and not just a chemical system.

The Gaia hypothesis states that the temperature of the planet, the oxidation state and other chemistry of all of the gases of the lower atmosphere (except helium, argon, and other nonreactive ones) are produced and maintained by the sum of life. We explored how this could be. How could the temperature of the planet be regulated by living beings? How could the atmospheric gas composition—the 20-percent oxygen and the one to two parts per million methane, for example—be actively maintained by living matter?

It took me days of conversation even to begin to understand Lovelock's thinking. My first response, just like that of the neo-Darwinists, was "business as usual." I would say, "Oh, you mean that organisms adapt to their environment." He would respond, very sweetly, "No, I don't mean that." Lovelock kept telling me what he really meant, and it was hard for me to listen. Since his was a new idea, he hadn't yet developed an appropriate vocabulary. Perhaps I helped him work out his explanations, but I did very little else.

The Gaia hypothesis is a biological idea, but it's not human-centered. Those who want Gaia to be an Earth goddess for a cuddly, furry human environment find no solace in it. They tend to be critical or to misunderstand. They can buy into the theory only by misinterpreting it. Some critics are worried that the Gaia hypothesis says the environment will respond to any insults done to it and the natural systems will take care of the problems. This, they maintain, gives industries a license to pollute. Yes, Gaia will take care of itself; yes, environmental excesses will be ameliorated, but it's likely that such restoration of the environment will occur in a world devoid of people.

Lovelock would say that Earth is an organism. I disagree with this phraseology. No organism eats its own waste. I prefer to say that Earth is an ecosystem, one continuous enormous ecosystem composed of many component ecosystems. Lovelock's position is to let the people believe that Earth is an organism, because if they think it is just a pile of rocks they kick it, ignore it, and mistreat it. If they think Earth is an organism, they'll tend to treat it with respect. To me, this is a helpful cop-out, not science. Yet I do agree with Lovelock when he claims that most of the things scientists do are not science either. And I realize that by taking the stance he does he is more effective than I am in communicating Gaian ideas.

If science doesn't fit in with the cultural milieu, people dismiss science, they never reject their cultural milieu! If we are involved in science of which some aspects are not commensurate with the cultural milieu, then we are told that our science is flawed. I suspect that all people have cultural concepts into which science must fit. Although I try to recognize these biases in myself, I'm sure I cannot entirely avoid them. I try to focus on the direct observational aspects of science.

Gaia is a tough bitch—a system that has worked for over three billion years without people. This planet's surface and its atmosphere and environment will continue to evolve long after people and prejudice are gone.

DANIEL C. DENNETT: One of the most beautiful ideas I've ever encountered is Lynn Margulis's idea about the birth of the eukaryotic cell through a transformation of what started out as a parasitic infestation of one cell by another. When she first proposed it, she was scoffed at, laughed at, and it's delicious that this is now pretty well accepted as a major, major theoretical development. I think of her as one of the heroes of twentieth-century biology.

Some of her recent popular writing disturbs me, because I think she's trying to take that wonderful idea and harness it as a political idea, stressing cooperation over competition. But that seems to me to be a mistake. Yes, the eukaryotic revolution was an instance in which what began as competition evolved into what is fundamentally a cooperative arrangement. That's its beauty, but precisely what it doesn't show is that cooperation is the norm or that cooperation is always good or that it's always possible. It's the rare and wonderful thing that enabled multicellular life to take off. But you can't read into it any message such as that nature is fundamentally cooperation; it isn't.

GEORGE C. WILLIAMS: I'm probably being unfair, but I would say that Lynn Margulis is very much afflicted with a kind of "God-is-good" syndrome, in that she wants to look out there at nature and see something benign and benevolent and ultimately wholesome and worth having. Whereas I look out there with Tennyson and see things red in tooth and claw. In other words, it's a bloody mess out there.

She likes to look out there and see cooperation and things being nice to each other. This culminates in this Gaia idea. There's this entity—we will not make it a god or a goddess, let's say that the implication is just a metaphor. But that's what she wants to see, and therefore, come what may, that's what she's going to see. She could say the same about me—that I think "God is evil," and I look out there at His creations and see nothing but evil. Time will tell, and will show that my approach is more fruitful in generating predictions about discoveries we're going to make.

LEE SMOLIN: Lynn Margulis has been for many years one of my scientific heroes. She is, in my opinion, one of the great living American scientists. She has this ability, which I think of as the characteristic of the best scientists from the American tradition, of thinking in broadly significant and original ways while staying very close to nature—to the ground, so to speak. Richard Feynman was another like this. You couldn't speak to him about physics without speaking about