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Acquiring Genomes by Lynn Margulis and Dorion Sagan. New York: Basic Books, 2002. xvi + 240pp. $28.00 (hardcover). ISBN 0465043917.

The immense complexity of the biosphere cries out for an explanation. In light of the tendency of inanimate objects to wind down over time, biologists have been searching for the origin of order in living forms (Kuppers, 1990; Weber et al., 1988). While the notion that a significant degree of organization can be obtained "for free" due to emergent properties implicit in complex systems (Kauffman, 1993) and the laws of physics and chemistry (Antonelli, 1985; Thompson & Whyte, 1942), the theory which gets the most press is Neo-

Darwinism. This paradigm for the emergence of complex living systems is a synthesis of Darwinian evolution by natural selection with modern genetics and molecular biology (Laszlo, 1987; Maynard Smith, 1998).

The basics of evolution rest on several fundamental points: (1) individuals reproduce and give rise to other creatures which are more similar to their parents than to other members of the population; (2) the reproduction is not perfect—errors are introduced and thus children are not identical to their parents; (3) reproductive resources (such as food) are limiting, forcing a competition where the most offspring are left by the creatures best suited to survival. These three observations are not controversial, and were well appreciated in Darwin's day. The bold (and, as it turns out, strikingly powerful) conjecture of evolutionary theory is this: when active over large populations and geological time scales, these three factors together are sufficient to account for all of the biological diversity we see in the natural world.

The question then becomes, what is the source of the reproductive variation, and in particular, the variation which can give rise to *better* adapted and more complex forms? As the authors of *Acquiring Genomes* point out, Darwin himself had no clear idea. Thanks to the advances of molecular biology and genetics, we now know a great deal about the mechanisms of inheritance and the changes which can potentially arise in DNA. However, the source of evolutionarily beneficial genetic changes remains controversial. The standard answer is random mutation and recombination (during sexual reproduction). Indeed, one of the authors' other books is an excellent treatment of the importance of sexual exchange of genetic material (Margulis & Sagan, 1986b). There are plenty of disagreements within this framework (such as regards punctuated equilibrium, for example), but most mainstream biologists agree that the basic paradigm is correct.

Nevertheless, it has been challenged on a number of fronts. A number of workers stress "Lamarckian" inheritance—the changing of the genome during the life of the individual (Jablonka & Lamb, 1995; Steele et al., 1999). This does indeed occur in a number of cases. But, crucially, this is not a fundamental blow to the Darwinian paradigm because (*contra* Lamarck) the changes are not correlated to lessons learned by the soma during its lifetime and thus do not contribute to future fitness in a teleological way. Can random (with respect to fitness) genetic change coupled with selection truly result in the wonder of the biological world? A number of arguments have been presented to suggest that it cannot (Denton, 1986; Behe, 1996; Gills et al., 2002); at the same time, the idea has been powerfully defended (Dawkins, 1995, 1996; Dawkins & Dennett, 1999).

Interestingly, some of the best evidence for the efficacy of this process comes from engineering and computer science. The advances of Artificial Life research (Langton, 1995) and genetic programming (Fogel et al., 2000; Koza, 1992, 1994) demonstrate that our intuitions about the power of natural selection are woefully inadequate. Anyone who has ever tried to write a computer program would, *a priori*, laugh at the idea that a working program could be written by selecting among randomly altered pieces of code. This is the same intuition that motivates the view that complex biological systems could not possibly have arisen "by chance". However, the field of evolutionary computation has proven that, counter to expectations, it is indeed possible to successfully evolve working computer programs by selection and completely random mutation. This is a direct engineering application of Darwinism, and a powerful counterpoint to critics who claim that the theory is untestable or circular.

Lynn Margulis and Dorion Sagan are the authors of a number of good books addressing important topics in this field (Margulis & Sagan, 1986a, 1991, 2000). In *Acquiring Genomes,* they present their view on the source of evolutionarily important genetic innovation. They do not dispute that random mutations occur. Rather, they propose an emphasis shift: their thesis is that a key source of biological complexity arises from horizontal transfer of whole genomes—the large-scale exchange of genetic material between unrelated individuals. In particular, the mechanism of symbiosis is a key factor in such exchanges, and one of the authors has contributed greatly in prior works to bringing biologists' attention to this important phenomenon (Margulis, 1981, 1998; Margulis & Fester, 1991).

The authors' dissatisfaction with random inherited changes is plausible not because of the (probably wrong but persistent) intuition about the lack of power of such a mechanism; rather, as they point out, it is a little-discussed fact that biologists often make random changes (such as in mutagenesis screens) in a number of different organisms and never find new species or even new tissue/organ systems. Of course, the Neo-Darwinist will counter that the time scale and population sizes that can be achieved in the lab pale in comparison to those available to evolution, and that additive changes coupled with selection will do the trick. The authors do not discuss the fact that indeed we can now mutate individual genes which do result in large-scale effects on the morphology of the organism (Lawrence, 1992). For example, specific targeting of top-level control genes can result in eyes or antennas developing in abnormal locations, as well as induce extra body segments or ectopic limbs.

Moving beyond criticism of Neo-Darwinism, the authors suggest a possible candidate for the origin of complexity: the acquisition of genomes through symbiosis. This kind of horizontal inheritance is Lamarckian in the right sense (no teleology governs the alteration of the somatic genome). As part of this proposal, the authors also present a novel definition of the problematic concept of "species": two organisms are of the same species if they contain the same genome sets. The authors rightly point out that one common definition of species—"reproductive compatibility"—is mainly suitable for larger "animals", and is completely inapplicable to many organisms such as bacteria. This is not a quibble over words: the definition of species is key because the mechanisms of speciation (origin of novel species) is a major lynchpin of any theory of evolution. Thus, the authors suggest that speciation is driven by the exchange of genomic material between organisms.

This is a very well-written book and gives many fascinating examples of symbiosis and symbiogenesis, such as slugs which do not need to eat but survive by photosynthesis. It does not include any references to primary scientific publications. A general bibliography, however, is provided and contains references to many works related to the authors' hypothesis. The novel perspectives on genomics and the definition of species which are provided by an emphasis on symbiosis are a very important addition to the mental repertoire of people who enjoy thinking about the fundamentals of biology.

So in the end, what is the evidence that species arise from horizontal genomic transfer and not from mutation? The details are presumably given in specialist papers, and while the book is an interesting list of examples, by itself it does not quite do the job of convincing the reader that the mechanism proposed by the authors is the main source of complexity and evolutionary innovation, especially for animals such as vertebrates. Interestingly, unlike many proposals in this field, their model is empirically testable. It will be interesting to see if the genetic programming community is able to make use of symbiotic genomic transfer in breaching the current stalemate that plagues the use of genetic algorithms to provide scalable solutions to real-world problems.

What of the source of the information content of complex animal forms? The "panspermia" hypothesis (Hoyle & Wickramasinghe, 2000) of the origin of life on earth suffers from the criticism that it only postpones the crucial question: if life on earth originally came from space, where did that life come from in the first place? Similarly, while symbiotic genomic exchange is an ideal and very exciting mechanism for providing novel metabolic pathways, it is perhaps a bit unsatisfying for higher morphologies. If biological innovation really is mostly due to acquisition of existing genomic information (via symbiosis from living creatures), where does the morphology of complex organ and tissue systems originate in the first place? While the authors describe some "higher" forms (such as cows and their digestive symbionts), the discussion is mostly focused on metabolism, and I would have welcomed more of an introduction to their views on the mechanisms of the origins of complex metazoan morphologies.

An interesting component of this book is an introduction by one of the leading figures in Neo-Darwinist thought: Ernst Mayr. His opinion, in a nutshell, is that the emphasis of the book is very valuable, but that genomic exchange via symbiosis is not the major driving force of evolution. He rightly points out that one of the most valuable features of this book is that it introduces the wonders of the microbial world, which provides many insights not available to those restricting their attention to large animals and plants (Horikoshi & Grant, 1998). Dr. Mayr also comments on a number of specific issues in the book, and this made me wish for an extra chapter consisting of a specific focused dialogue (or debate) between him and the authors.

Strikingly, on page xiii of the introduction, one finds this: "Let the readers ignore those [interpretations] that are clearly in conflict with the findings of modern biology." I find this to be a fairly odd suggestion, and it seems that perhaps those interpretations which are in conflict with established thought are often the most interesting and worthy of consideration; this is especially true when the theories come from a source such as the authors of this book, who have a proven track record of important contributions to biology. Those interested in making important breakthroughs are particularly to be cautioned against uniformly rejecting anything which contradicts “established thought”.

I found a couple of specific points of contention with a few things in this very thought-provoking book. First, the authors spend some time discussing the meta-science of relevant terminology. On pages 15–18, the authors state that “anthropomorphic terms such as ‘competition’ have no place in scientific discourse”. For example they suggest that Dawkins’ “meme” is not a valid term. I would argue that this is deeply wrong. Much like the concept of the intentional stance in cognitive science (Dennett, 1987), such concepts are scientific to the extent that they provide mathematically compact formulations of empirical data and help to generate predictive and testable models. This can be said of many of the terms in the table on page 20, which the authors say are “deficient and pseudoscientific terms” because “no quantitative measure exists”. Moreover, on page 135, one reads: “the metaphor of Gaia as an ancient strong-willed goddess allowed Lovelock to write about Earth’s history in a fashion accessible to readers”. Are the nets down for such metaphors or not? Surely the notion of “Gaia as goddess” is not a more scientific or quantitative construct than “competition for resources”. Metaphors are useful to the extent to which they allow further inquiry, and “competition” (and many of the terms in the table) can be formulated in neutral, objective, productive ways.

Another controversial point in the book is the attack on the concept of “evolutionary progress”. It is certainly true that more complex creatures are not necessarily more (or less) fit than less complex life forms: complexity is not by necessity aligned with reproductive success. But it is also impossible to deny that over time, the complexity of members of the biosphere has increased. It is clear that in a well-defined morphological sense, a man is more complex than a bacterium. As the authors point out, the bacteria have the upper hand (by far) in terms of metabolic sophistication and sheer reproductive success. If anything, this observation further strengthens the mystery: if bacteria were doing so well, what exactly is responsible for the appearance of more complex forms? The “why” question is as relevant as the “how”.

Finally, in the age of unceasing arguments over cloning and many other biomedical ethics dilemmas, it is important to place biology in a greater context. “The ape who is nearly hairless, the one who cuts down rain forests with abandon, is deluded by visions of his importance” (p. xvi) subtly suggests a conflation of moral superiority with metabolic sophistication. In precisely what way is the vision of human uniqueness a delusion? Ecologically motivated post-modern attempts to equalize human beings with all other forms of life are highly questionable, despite reasonable concerns over the health of our environment. The genome and resulting biochemical pathways are not the be-all and end-all of our existence. The genomics are responsible for the construction of our bodies, but in the end we are moral and rational beings. Bacteria may have the upper hand in ways of manipulating metabolic compounds, but respect for the wonders of biological mechanisms should not overshadow common sense about the value of rationality, moral reasoning, and intelligence. Even strict determinist materialists must make choices every day, and it is important to consider that the genomics constrain our bodies but do not determine the contents of our minds (Lucas, 1961, 1991; Penrose, 1991, 1996). As human beings, we have unique possibilities and responsibilities (Adler, 1993), such as the environmentalism to which the authors allude.

I highly recommend this book to anyone who is interested in biology, and especially in the origins of life's innovative solutions to the business of staying alive. The question of whether horizontal transfer via symbiosis is a major cause of evolutionary novelty is still open. If random mutation is insufficient, and if the "made by God" hypothesis lacks experimental utility, what's left? The layer between the genotype and the phenotype—embryonic development—is now beginning to be unraveled. The complexity and systems-theory properties of developmental morphogenesis are likely to provide crucial future insights into what mechanisms may plausibly underlie beneficial changes in biological form (Raff, 1996; Raff & Raff, 1987; Thomson, 1988).

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The Deep Hot Biosphere by Thomas Gold. New York: Copernicus Books, 2001. 243 pp. $20.00 (paperback). ISBN 0-387-95253-5.

There is much to be said about this important book, not only in the technical fields of geology, biology, and energy resources, but also in what it tells us about science and the social context in which science operates.