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How the Leopard Changed Its Spots

The Evolution of Complexity

Brian Goodwin

WITH A NEW PREFACE BY THE AUTHOR

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PREFACE

to the Princeton Science Library Edition

In the six years since the first edition of *How the Leopard Changed Its Spots*, much has changed in biology, its applications, and its broader connections with human values. Some of these changes have been fairly predictable, others much less so. Predictably, genetics has continued to plow ever deeper furrows into the soil of life, revealing in increasing detail the genetic roots that lie beneath the processes of embryonic development and how genes have changed during evolution. This knowledge provides us with the possibility of greatly extending our control over the species that serve humanity, such as sheep, pigs, salmon, and the plants used in agriculture, by redesigning their genomes. The Human Genome Project is essentially complete, opening the door to what is regarded by many as a virtually unlimited transformation of the human species in terms of increased fitness—improved health, increased longevity, and greater reproductive potential. We are currently living through the greatest intellectual moment in history, according to a recent author, whose chromosomes appear on the cover of his book. The genes on these chromosomes do not belong to him, however. They are owned by the biotechnology and pharmaceutical companies which have patented them, under new laws that have transformed in recent years the very meaning and purpose of a patent. All life is now up for auction. Truly, we live in interesting times.

There is a sense of destiny in the air, a realization that we have reached a decisive moment in our history when we need all our wits to negotiate a passage into a sustainable future with a good quality of life for all, human and nonhuman alike. Of course, our science will continue to serve us as it has in the past, opening up technological possibilities, and biotechnology is the new frontier. It is now evident, however, that a development has taken place that was not foreseen six years ago. This is the expression of a widespread public unease about the implications of genetic manipulation of farm animals and crop plants because of health and ecological issues. Is this a safe technology? It is precisely here that the perspective presented in *How the Leopard Changed Its Spots* is relevant. Genes make sense only within the context of the whole organism, and organisms make sense only within the context of the ecology in which they belong. Reductionist biology is a powerful analytical tool, but the intrinsic complexities of life mean that the consequences of genetic and ecological manipulation are forever unpredictable. This is one of the first lessons of the "sciences of complexity," which have continued to strengthen and grow throughout the past decade, developing scientific tools for describing the emergent properties of life, such as the health of organisms and the pattern of species abundance in natural ecosystems. My colleague Ricard Solé and I have examined these in a book entitled *Signs of Life: How Complexity Pervades Biology* (New York: Basic Books, 2000). The unpredictable responses of complex systems to change of conditions is a fact of life, and this has profound implications for the way in which we practice the science of complexity and apply the knowledge we gain from it.

The last chapter of *Leopard* explores what I call "a science of qualities," in connection with issues relating to quality of life. I argue that complex wholes such as organisms, communities, and ecosystems manifest their emergent properties through qualities as well as quantities. We need to take account of this in attempting to understand and relate to the wholes on which our lives depend. This is what the public is demanding, I believe, in connection with healthy food, sustainable agriculture, and diverse ecosystems. Scientists do not know how to respond to these demands because all qualities have to be reduced to measurable quantities to be regarded as objectively, scientifically "real." A good farmer, however, recognizes the quality of soil independently of whether it has all the recommended levels of nitrates, phosphates, sulfates, and so on, that scientists define as the basic chemical needs of crop plants. If, for example, the microbes, the mycorrhizal fungal network, and the worms have gone, poisoned by excess chemicals, then the texture and quality of the soil are clearly deficient to a discerning farmer, one who relates directly to the land. The same applies to farm animals, who in their own right, and for healthy food, require a good quality of life. But how can science respond to this need if there is no way of reliably assessing qualities?

Recent studies have shown that anyone can be good at assessing the quality of life of farm animals. At the very end of *Leopard*, I mention the research of Françoise Wemelsfelder on animal welfare. She has now demonstrated that people are very good at evaluating the quality of experience of pigs. No quantities are involved, and no experience with the animals is required. People can also discriminate between pigs that have been living in a deprived environment and those from an enriched one. We ought not to be surprised at this. We live our lives primarily through the evaluation of qualities—in our relationships with other people, in the first place, but also with animals, landscape, and life in general. Quality is what we live for. Western science has, for historical and ideological reasons, chosen to focus on quantities, while the sciences of other cultures have tended to focus much more on qualities. Our science has given us remarkable insights into natural processes, and we have learned to control these in our technologies: electromagnetic devices such as lights, motors, computers, radio, and television; chemical processes involved in the production of paints, synthetic fabrics, herbicides and pesticides, and drugs, to name but a few. But when it comes to life, the application of a science of quantities is limited, and we keep reaching boundaries. Attempts to control ecosystems, economies, communities, plants, animals, and health have all resulted in unexpected problems, unforeseen difficulties, which we now understand to be direct consequences of their complexity, their intrinsic unpredictability.

A new frontier is now opening for our culture, a frontier where science will continue to be relevant, but in a radically altered form. Instead of a primary focus on controlling quantities, the challenge for science is to cooperate with the natural creative dynamic that operates at the edge of chaos, to experience the qualities that emerge there, and to move toward a participatory worldview which recognizes the intrinsic values that make life worthwhile. Many people are exploring what this means in different contexts—in healthcare, environmental action, the corporate sector, and science itself. This seems to be how the leopard is now changing its spots.

preface

Scientific theories develop out of choices and assumptions that are neither arbitrary nor inevitable. Darwin made particular assumptions about the properties of organisms and their evolution that have led to one of the most successful theories ever to have emerged in science. He accepted that the major phenomenon of life that needs to be accounted for is the adaptation of organisms to their habitats, and he believed that this could be explained in terms of random hereditary variations among the members of a species and natural selection of the better variants over long periods of evolutionary time. This has become the basis for explaining all aspects of life on earth, or elsewhere. No aspect of human life is untouched by Darwin's theory of evolution, modified in various ways to apply to economics and politics, to the explanation of the origins and the significance of art, and even to the history of ideas themselves.

However, all theories carry with them a particular viewpoint, a way of seeing phenomena that produces sharp focus on certain aspects of reality and blurred vision elsewhere. A striking paradox that has emerged from Darwin's way of approaching biological questions is that organisms, which he took to be primary examples of living nature, have faded away to the point where they no longer exist as fundamental and irreducible units of life. Organisms have been replaced by genes and their products as the basic elements of biological reality. This may seem to fly in the face of all common sense, but stranger things have happened in the name of science. What's more, there is no lack of highly persuasive books whose objective is to demonstrate why organisms are not what they seem to be—integrated entities with lives and natures of their own—but complex molecular machines controlled by the genes carried within them, bearers of the historical record of the species to which the organism belongs. Though this is certainly not what he anticipated, this is in fact the sharp focus that has developed from Darwin's assumptions about the nature of life, and there is no denying the remarkable insights that have accompanied this illumination of the molecular level of organisms.

There is always a price to be paid for excessive preoccupation with one aspect of reality. Modern biology has come to occupy an extreme position in the spectrum of the sciences, dominated by historical explanations in terms of the evolutionary adventures of genes and an associated single-level molecular reductionism of gene products. Physics, on the other hand, has developed explanations of different levels of reality, microscopic and macroscopic, in terms of theories appropriate to these levels, such as quantum mechanics for the behavior of microscopic particles (photons, electrons, quarks) and hydrodynamics for the behavior of macroscopic liquids. It is the absence of any theory of organisms as distinctive entities in their own right, with a characteristic type of dynamic order and organization, that has resulted in their disappearance from the basic conceptual structure of modern biology. They have succumbed to the onslaught of an overwhelming molecular reductionism.

Here we face another curious consequence of Darwin's way of looking at life: despite the power of molecular genetics to reveal the hereditary essences of organisms, the large scale aspects of evolution remain unexplained, including the origin of species. There is "no clear evidence . . . for the gradual emergence of any evolutionary novelty," says Ernst Mayr, one of the most eminent of contemporary evolutionary biologists. New types of organisms simply appear upon the evolutionary scene, persist for various periods of time, and then become extinct. So Darwin's assumption that the tree of life is a consequence of the gradual accumulation of small hereditary differences appears to be without significant support. Some other process is responsible for the emergent properties of life, those distinctive features that separate one group of organisms from another—fishes and amphibians, worms and insects, horsetails and grasses. Clearly something is missing from biology. It appears that Darwin's theory works for the small-scale aspects of evolution: it can explain the variations and the adaptations within species that produce fine-tuning of varieties to different habitats. The large-scale differences of form between types of organism that are the foundation of biological classification systems seem to require another principle than natural selection operating on small variations, some process that gives rise to distinctly different forms of organism. This is the problem of emergent order in evolution, the origins of novel structures in organisms, which has always been one of the primary foci of attention in biology.

It is here that new theories, themselves recently emerged within mathematics and physics, offer significant insights into the origins of biological order and form. Whereas physicists have traditionally dealt with "simple" systems in the sense that they are made up of few *types* of components, and observed macroscopic (large scale) order is then explained in terms of uniform interactions between these components, biologists deal with systems (cells, organisms) that are hideously complex, with thousands of different types of genes and molecules all interacting in different ways. Or so it seems at the molecular level. However, what is being recognized within the "sciences of complexity," as studies of these highly diverse systems are called, is that there are characteristic types of order that emerge from the interactions of many different components. And the reason is not unlike what happens in "simple" physical systems. Despite the extreme diversity of genes and molecules in organisms, their interactions are limited so that distinctive types of order arise, especially in relation to the large-scale aspects of structure or morphology, and the patterns in time that constitute organismic behavior. A particularly striking property of these complex systems is that even chaotic behavior at one level of activity—molecules or cells or organisms—can give rise to distinctive order at the next level—morphology and behavior. This has resulted in one of the primary refrains of complex studies: order emerges out of chaos. The source of large scale order in biology may therefore be located in a distinctive type of complexity of the living state that is often described in terms of the computational capacity of the interacting components rather than their dynamic behavior. These terms, *computational* and *dynamic*, actually reflect different emphases and are not in conflict with one another. What has developed from the widespread use of computers to explore the dynamic potential of interacting systems that can process information, such as biological molecules, cells, or organisms, is a new theory of dynamical systems collectively referred to as *the sciences of complexity*, from which have developed significant branches such as artificial life.

In this book I explore the consequences of these ideas as they apply to our understanding of the emergence of biological forms in evolution, particularly the origin and nature of the morphological characteristics that distinguish different types of organism. These questions overlap those addressed by Darwin, but they focus on the large-scale, or global, aspects of biological form rather than on small-scale, local adaptations. As a result, there is no necessary conflict between the approaches, nor with the insights of modern biology into the genetic and molecular levels of organisms. These contribute to the construction of dynamical theories from which emerge higher level properties of biological form and the integrated behavior of organisms. Conflict arises only when there is confusion about what constitutes biological reality. I take the position that organisms are as real, as fundamental, and as irreducible as the molecules out of which they are made. They are a distinct level of emergent biological order, and the one to which we most immediately relate.

The recognition of the fundamental nature of organisms, connecting directly with our own natures as irreducible beings, has significant consequences regarding our attitude to the living realm. It is here that another aspect of scientific theories comes to the fore, one that is often regarded as irrelevant or secondary to the facts that science uncovers. Darwinism, like all theories, has distinct metaphorical associations that are familiar from the use of descriptive terms such as *survival of the fittest, competitive interactions* between species, *selfish genes, survival strategies,* even *war games* with *hawk and dove strategies.* Such metaphors are extremely important. They give meaning to scientific theories, and they encourage particular attitudes to the processes described—in the case of Darwinism, to the nature of the evolutionary process as predominantly driven by competition, survival, and selfishness. This makes sense to us in terms of our experience of our own culture and its values. Both culture and nature then become rooted in similar ways of seeing the world, which are shaped at a deeper level than metaphor by cultural myths, from which the metaphors arise. The consequences of this perspective have emerged particularly clearly in this century, especially in the view of species as arbitrary collections of genes that have passed the survival test. The criterion of value here is purely functional: either species work or they don't. They have no intrinsic value.

I shall argue that this view of species arises from a limited and inadequate view of the nature of organisms. The sciences of complexity lead to the construction of a dynamic theory of organisms as the primary source of the emergent properties of life that have been revealed in evolution. These properties are generated during the process known as *morphogenesis,* the development of the complex form of the adult organism from simple beginnings such as an egg or a bud. During morphogenesis, emergent order is generated by distinctive types of dynamic process in which genes play a significant but limited role. Morphogenesis is the source of emergent evolutionary properties, and it is the absence of a theory of organisms that includes this basic generative process that has resulted in both the disappearance of organisms from Darwinism and the failure to account for the origin of the emergent characteristics that identify species. Many people have recognized this limitation of Darwin's vision, and my own arguments are utterly dependent on their demonstration of the path to a more balanced biology. Primary among these is the towering achievement of D'Arcy Thompson in his book *On Growth and Form* (1917), in which he single-handedly defined the problem of biological form in mathematical terms and reestablished the organism as the dynamic vehicle of biological emergence. Once this is included in an extended view of the living process, the focus shifts from inheritance and natural selection to creative emergence as the central quality of the evolutionary process. Because organisms are primary loci of this distinctive quality of life, they become again the fundamental units of life, as they were for Darwin. Inheritance and natural selection continue to play significant roles in this expanded biology, but they become parts of a more comprehensive dynamical theory of life that is focused on the dynamics of emergent processes.

The consequences of this altered perspective are considerable, particularly in relation to the status of organisms, their creative potential, and the qualities of life. Organisms cease to be mere survival machines and assume intrinsic value, having worth in and of themselves, like works of art. Such a realization arises from an altered understanding of the nature of organisms as centers of autonomous action and creativity, connected with a causal agency that cannot be described as mechanical. It is relational order among components that matters more than material composition in living processes, so that emergent qualities predominate over quantities. This consequence extends to social structure, where relationships, creativity, and values are of primary significance. As a result, values enter fundamentally into the appreciation of the nature of life, and biology takes on the properties of a science of qualities. This is not in conflict with the predominant science of quantities, but it does have a different focus and emphasis.

Darwinism sees the living process in terms that emphasize competition, inheritance, selfishness, and survival as the driving forces of evolution. These are certainly aspects of the remarkable drama that includes our own history as a species. But it is a very incomplete and limited story, both scientifically and metaphorically, based on an inadequate view of organisms; and it invites us to act in a limited way as an evolved species in relation to our environment, which includes other cultures and species. These limitations have contributed to some of the difficulties we now face, such as the crises of environmental deterioration, pollution, decreasing standards of health and quality of life, and loss of communal values. But Darwinism shortchanges our biological natures. We are every bit as cooperative as we are competitive; as altruistic as we are selfish; as creative and playful as we are destructive and repetitive. And we are biologically grounded in relationships, which operate at all the different levels of our beings, as the basis of our natures as agents of creative evolutionary emergence, a property we share with all other species. These are not romantic yearnings and utopian ideals. They arise from a rethinking of our biological natures that is emerging from the sciences of complexity and is leading toward a science of qualities, which may help in our efforts to reach a more balanced relationship with the other members of our planetary society.

acknowledgments

I am indebted to so many people for the insights that form the basis of this book that I am tempted to say that not I, but this collection of friends and colleagues, wrote it. The people who have influenced me in developing these ideas include old and new relationships, though inevitably it is the older ones that have made the more lasting impact. Among these I must mention my longest working collaboration, with Gerry Webster, which started over twenty years ago when we were both at the University of Sussex, where we discussed at length what seemed to us the deeper levels of biological meaning, involving many students in the process. Another very important influence from that time was John Maynard Smith, whose clarity of thinking about biological matters always forced Gerry and me to go further into conceptual detail than we might otherwise have done. However, John would certainly not thank me for implicating him in the direction and the conclusions of this book. The same is true of Lewis Wolpert, an old colleague whose work has been a stimulus to clarification of the alternative views on morphogenesis and evolution that are presented here. On the other hand, an equally long working friendship with Stuart Kauffman has involved a continuous convergence of ideas that, despite quite different analytical modes and emphases, has led us to virtually identical conclusions, from which I take great satisfaction and a deepened belief that we are onto a promising track.

In more recent years the influences have come from colleagues at the Open University, particularly from an ongoing dialogue with Mae-Wan Ho, whose thinking and imagination know no boundaries and continually challenge accepted limitations. I am also indebted to Steven

Rose for a dialectic about biology and society that maintained a broad perspective. We diverge more in emphasis than in objectives. For very useful comments on various chapters I am indebted to Hazel Goodwin, Jane Henry, Alastair Matheson, Jennifer Wimborne, and Françoise Wemelsfelder.

As for the many other people whose work and ideas have influenced me, I have to acknowledge them collectively here and specifically by reference in the text itself. Science is a collective enterprise, an outcome of the type of relational order that underlies all creative activity, so my own contribution is minimal. However, someone has to take responsibility for the limitations of the work, and that can only be me. My grateful thanks go to all those with whom it has been my privilege to interact over the years.

How the Leopard Changed Its Spots

chapter 1

Whatever Happened to Organisms?

Something very curious and interesting has happened to biology in recent years. Organisms have disappeared as the fundamental units of life. In their place we now have genes, which have taken over all the basic properties that used to characterize living organisms. Genes multiply by making more copies of themselves; they vary by mutation; they evolve by competitive interaction, the better versions increasing in number at the expense of less useful variants. And in addition to all this, genes make organisms as a means of exploiting different environments over the face of the earth so that they can increase and prosper. Better organisms made by better genes are the survivors in the lottery of life. But behind the front that we see as the living, behaving, reproducing organism is a gang of genes that is in control. They alone persist from one generation to the next and so evolve. The organism itself is mortal, dying after a mere generation, whereas the genes are potentially immortal, the living stream of heredity that is the essence of life.

This is the biology we all know and many love, the legacy of Charles Darwin's vision of life as chance variation in the hereditary material of organisms and as persistence of the better variants via natural selection. It is a beautifully simple and elegant story of how the various types of organisms that we see about us, and the fossil forms that have left their traces, come into being and pass away, told now in terms of the adventures of their genes. This leads naturally and inevitably to the conclusion that, to understand everything that is essential about organisms, what we need to know is the information in their genes. Then we would be able to compute the adult organism in all its details of form and function, in the same way that we can predict the output of a computer from the information contained in the program it is given to read. This is why organisms have vanished from biology as the fundamental units of life, replaced by genes as their most basic and important components.

This genocentric biology is a perfectly logical consequence of the way Darwin chose to describe evolution in terms of inheritance, random variation, natural selection, and the survival of adapted species. Of course Darwin did not foresee how this story would unfold, and there were crucial changes to his ideas of inheritance that had to be made before genetics could flower into the extraordinarily powerful science that it has become in this century. There is no denying the insights that have been gained from the study of the remarkable properties of the genetic material of living organisms, DNA (deoxyribonucleic acid). But in science there is always the danger that a particular way of looking at a subject can result in tunnel vision—the assumption that it can explain everything, an inability to recognize the limitations of the approach, and reluctance to entertain other possibilities. This is what has happened in genocentric biology. It is just like the story of geocentric cosmology—the old idea that the Earth is the center of the cosmos, with all the planets and stars rotating about us. This theory worked perfectly well for a long time, and explained nearly all the