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THE EQUATIONS of LIFE

The Hidden Rules Shaping Evolution

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Image of Lesser Mole-Rat (*Nannospalax leucodon*)
by Maksim Yakovlev.

PREFACE

SOME OF THE MOST fascinating questions whose answers still remain obscure to science lie at the interface between traditional fields. Of course, disciplines are not real entities. They are artificial constructs made by people. Collecting scientific questions into neat disciplinary boxes is administratively useful but artificial and sometimes intellectually counterproductive. The unguided processes of the cosmos do not recognize these neat divisions, either. There is just the universe, about which a civilization can ask questions.

This book explores one line of thinking that tries to make sense of diverse areas of science that straddle the living and the nonliving, the indefeasible links between physics and evolutionary biology. The connections reflect the reality that life is just a form of reproducing, evolving matter in a universe with many interesting and distinctive types of matter.

The reader should know from the outset that this book is not a sterile attempt to demonstrate that evolution is an utterly predictable product of physics. Historical quirks and chance do play a part, and that point is indisputable. They result in the remarkable plethora of detail and the kaleidoscope of forms that we observe in the great evolutionary experiment occurring on our planet. Travel to the Indonesian islands of Lombok and Bali, and despite their similar size, location, and a mere thirty-five kilometers between them, the fauna of each island is distinct. Life on the islands is the evolutionary progeny of that invisible Wallace Line that carves through the deep waters of the Lombok Strait, placing Bali within the historical trajectory of Southeast Asia's particular evolutionary journey. Bali's forests echo with the calls of Asian woodpeckers and barbets, while Lombok, alive with the shrill cries of cockatoos and honeyeaters, lies within the fold of Australasia's evolutionary umbrella. But lurking within this riot of evolutionary experimentation are unyielding principles of physics. It is those that concern me in this book, principles that have increasingly explained many facets of biology, from the subatomic scale to whole populations—biological observations that were previously assumed to be flukes of history and beyond prediction.

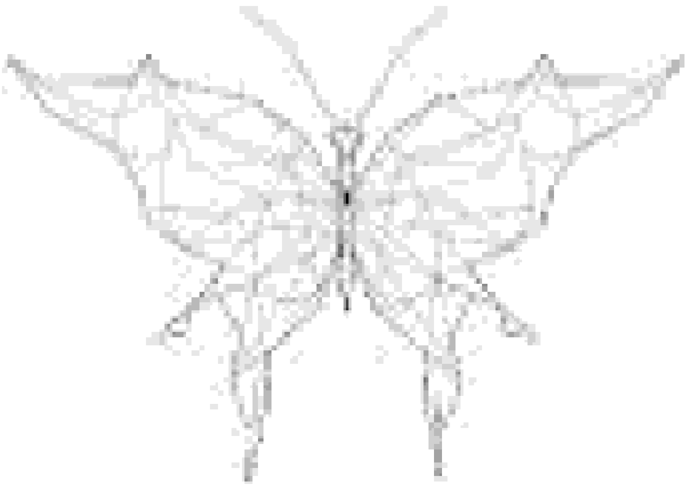
Which features of life are deterministically driven by physical laws and which are mere chance, contingent events decided by a metaphorical role of the dice? This question remains one of the most cogent and interesting puzzles about life and its evolution. I do not intend to provide a definitive answer to this question; I'm not convinced anyone currently has the knowledge to do so. However, I do intend to shed light on the growing understanding of the principles that channel life at all levels of its structure and how this expanding corpus of work shows that life is firmly embedded within the basic laws that shape all types of matter in the universe, much more so than a cursory glance at the menagerie on Earth might suggest.

From this view of life emerge conclusions that some people might find sobering, others might find frightening, and still others thrillingly comforting. For people who share with me a fascination for life on Earth, there is something reassuring about our increasing ability to demonstrate that the apparently fathomless profusion of living things on this planet conforms to simple principles that apply to all other types of matter. For those people who also enjoy speculating about what life on other planets might look like (if it exists at all), a conclusion might be that at all levels of its structural hierarchy, alien life is likely to look strangely similar to the life we know on Earth.

As we let go of many of our ancient traditions of thought that have separated life from inanimate matter, we may find that our fear that this will dangerously consign people and other creatures to what is often viewed as the blandness of physics that determines the fate of most matter in the universe is unfounded. Instead, the unity of evolution and physics brings a new richness to our view of life, an appreciation that within the simplicity of rules that govern and limit the forms of living things there is remarkable beauty.

CHAPTER 1

LIFE’S SILENT COMMANDER



A SHORT WALK THROUGH the Meadows in Edinburgh would leave most people in little doubt that life on Earth is a remarkable anomaly in a universe of bland conformity. Trees of various shades of green rustle in the wind, birds take to the air in gymnastics that left the ancients aghast at the agility of these heavier-than-air flying machines, and along the ground run all manner of animals; the smallest ladybugs land on picnicking tourists, while domestic dogs leap and cavort across the grass.

Compare this spectacle with the velvet black emptiness of space seen with some of our best telescopes. Images of galaxies colliding in astrophysical violence, the light of these long-since-dead encounters collected after traveling billions of years through an empty void almost unimpeded. In this vast, infinite vacuum, punctuated by a collection of stars, planets would materialize. And on one planet, tourists would be swatting flies in a meadow below a castle. What could be more of a contrast between the apparently simple laws that govern the gravitational rotation of a collection of stars—

mere balls of fusing gas in the rarefied expanse of space with their attendant planets—and the unpredictable leaps and bounds in something as complex as a pet Labrador, the phenomenon of life?

I once heard a distinguished astrophysicist declare that he was glad to be studying stars, since a star is much easier to understand than an insect.

As we peer into outer space, we can certainly find merit and empathy in this view. Even at the intimidating scale of a massive star, we find simplicity. As the star burns, fusing gaseous elements and releasing energy, so these building blocks successively grow in atomic mass. We begin with hydrogen atoms, the universe's most abundant element, which joins with other hydrogen atoms to form helium. Other helium atoms combine to form carbon and so on, until successive layers are formed—oxygen, neon, magnesium; the atomic mass of the elements grow as the products of each new round of fusion are formed. In the center of the star is iron, which cannot fuse to form any other elements. Iron is the last stage of fusion, and the result of this sequence of relatively simple atomic additions is layer upon layer of heavier and heavier elements from the surface to the core of the star. Elements heavier than iron are formed by other means, such as in the catastrophically energetic explosions of stars that herald the spectacle of a supernova.

Compare the onion-like arrangement of elements in a massive star, over a million kilometers in diameter, to our ladybug (a *ladybird* in many places in the world), just seven millimeters long, sitting on the thumbnail of a sleeping tourist in the Meadows.

The little oval ladybug, a beetle, is just one insect among many species that inhabit the planet. (We do not know how many species there are. About a million are known, and there are likely to be many more still undiscovered.) However, this unassuming creature is full of complexity and comprises eight major parts. Its head is one discrete portion and contains its mouth. The ladybug has antennae and eyes for sensing the world around it, with the antennae considered a separate part. The pronotum, a tough protrusion behind the head, protects it from damage. Behind this are the thorax and abdomen, the body section to which the wings and legs are attached. Finally, this complex machine has elytra, wing cases that protect its vulnerable and delicate flying apparatus.

Yet like the star, each of these features is molded by physical laws. The power of flight conferred by wings means the ladybug must observe the laws that govern aerodynamics, as must all flying creatures. And as for its legs—well, why not wheels? Like all land animals, besides snakes and some lizards that lack limbs altogether, ladybugs evolved legs instead of wheels. There are physical reasons for that, rooted in the relative effectiveness of legs in navigating the irregular terrain of our planet. In protecting their gossamer wings, the elytra must observe rules that pertain to the behavior of tough materials, such as abrasion resistance and flexibility.

In all segments of the ladybug, we can identify the principles of physics. The apparent complexity of the ladybug compared with a star lies merely in the greater number and variety of principles embedded within the insect and which it uses to live its life. Evolution is simply a very good process for assembling different principles, which we can represent as equations, into an organism. Any natural environment usually presents multiple challenges to survival. If a physical process leads to a living thing's development of a characteristic that makes the living entity less likely to be eliminated before it reproduces (reproduction being the measure of evolutionary success), then creatures will evolve over time and can be thought of as containers manifesting diverse physical laws.

The menagerie of life, impressive enough even on a casual walk in the Meadows, grows in variety as you explore its forms through time. Equipped with every scientist's favorite improbable toy, the time machine, we might revisit the Meadows 70 million years ago. Then, we would find forms of life very different from today. Like modern birds, the reptilian pterodactyls had mastered aerodynamics, some with ten-meter wingspans. Feathered dinosaurs and strange insects roamed the land, and in ponds or lakes, reptiles, slender and long, achieved mastery in their watery habitats. If we hop back into our machine and return to about 400 to 350 million years ago, we would find Edinburgh in the site of immense volcanic activity, thick mat-like conglomerations of microbes growing here and there. Across the land, between the volcanic cones, the earliest land plants, the *Cooksonia*, stake their claim to the new habitat. Scurrying among their short knobbly stems of just a few centimeters' height were early insects and the now extinct eight-legged beetle-like trigonotarbids. Return just a few tens of millions of years later and you would have seen four-legged *Pederpes*, a forerunner to modern land vertebrates, awkwardly shifting its one-meter-long slithery body through the undergrowth, peering this way and that with its triangular head to chart its way through.

But impressed though we may be with all the wonderful life forms we have observed in our excursion through time, there is a strange familiarity about all these living things. Their shapes and forms, although different, share fundamentally the same types of solutions to living as we see in modern forms. These similarities are not merely an artifact of evolutionary descent. The growth of early plants against gravity, the size of bones that hold up a dinosaur, the sleek shapes of water-bound animals, and the features of wings that allow a pterodactyl to fly lead to evolutionary forms similar to modern-day organisms faced with the same unyielding laws.

The complexity and sheer diversity of life in time and space could convince anyone that life represents something quintessentially different from physical processes, a divergence of form that transcends the simple principles that seem to fashion the apparently predictable structure of the inanimate world.

Yet physical laws restrictively drive life toward particular solutions at all levels of its assembly. The outcomes are not always predictable, but they are limited. It does not matter at what level those requirements are operating, from the subatomic to the population scale: the results are various, but not boundless.

Even at the smallest scale, we can see these narrow channels of evolution. Consider molecules, such as the proteins, from which the eclectic mixture of monsters on Earth is assembled. Like life at the larger scale, proteins do not display untrammeled potential. Rather, in observing the limited ways that proteins (including enzymes, biological catalysts) can be folded together, some scientists have argued that these configurations reflect a set of forms analogous to the perfect and unchanging forms of things espoused by Plato. To some people, such a view seems to contradict the Darwinian view of life, which emphasizes natural selection's tendency to produce apparently unlimited variety.

Science can sometimes be unnecessarily polarized, and, of course, challenging the Darwinian view is always popular, edgy, and controversial. In the synthesis I present here, there is no challenge to Darwin's basic precept that natural selection can fashion an extraordinary range of creatures or even proteins. I merely illustrate how this process is limited in the basic pattern of its products, not just at the level of the organism, but in any part of its construction, from populations down to proteins and down to the atomic level. I gather evidence from what has become an impressive corpus of work by many researchers to show how physical principles sharply narrow the scope of the evolutionary process at all levels of life's structure.

My view is underpinned by a simple proposition. Evolution is the process by which the environment acts as a filter to select units of organic mass in which a mosaic of interacting physical laws are optimized sufficiently to allow for reproductive success. The environment in this context can include a whole range of challenges—from weather phenomena such as storms to the appetites of predators—that might prevent an organism from reproducing. Evolution is just a tremendous and exciting interplay of physical principles encoded in genetic material. The limited number of these principles, expressed in equations, means that the finale of this process is also restrained and universal.

Equations are merely a means to express in mathematical notation the physical processes that describe certain aspects of the universe, including features of living things. The phrase *equations of life* is shorthand for this growing capacity to use physical processes, and often their mathematical formulations, to describe life at different levels of its hierarchy. Throughout this book, I will provide some examples of these equations, but I do not expect you, the reader, to have to understand their nuances and details or how to use them. I show them to illustrate how physical principles that underlie evolution can often be expressed in these conveniently shortened mathematical forms.

That the laws of physics should bound life is hardly a controversial statement. The ladybug in the Meadows does not exist outside the same principles that govern the formation of the Sun that warms it on a sunny day. Life is very much part of the universe: it cannot operate outside its rules. Yet although this observation seems trite, we are often remarkably unwilling to accept the extent to which life is tightly constrained by physical laws. When observing living things, we can easily forget that the rules that govern their architecture set a harsh perimeter; the extravagance of life can appear, to the unreflective observer, to be limitless in its variety.

For me, what is surprising about the journey through the different scales of life's structure, accompanied by our growing knowledge, is that life is much more amenable to description in terms of physical processes, and thus simple mathematical relationships, than once was thought, and that these principles are now being elaborated at many different levels of its hierarchy. These insights also suggest that life is much more narrowly circumscribed than those who favor the role of chance and history would like to think. Accordingly, life is more predictable and potentially universal in its structure than is sometimes assumed.

In their details, living things do show apparently illimitable embellishments. The vastness in the details of living things has probably caused a divergence between the biological and physical view of the universe. Yet if we return to our facile observation that biology operates within the laws of physics, then we should be able to more comprehensively reconcile this division.

When I joined a university physics department a few years ago as an astrobiologist, I was asked to teach an undergraduate physics course called Properties of Matter. For me, with a background in biochemistry and biology, a semester of this material would be unpalatable without some biology, so I set about modifying my task by using biological examples to illustrate the physical laws and ideas I needed to teach. The inclusion of some biology improved my own motivation, and I also thought that doing so would be interesting for undergraduates.

It was not a difficult task to find these examples. At the molecular level, the van der Waals forces that hold molecules together—these feeble forces from the inherent polarity in molecules make the molecules behave like little bar magnets (even the unreactive noble gases such as neon can behave like this)—can be illustrated with a gecko. These agile desert lizards have an abundance of tiny hairs on their toes; the hairs allow the combined van der Waals forces on all four feet to hold the creature fast on a vertical surface, allowing it to run up a shiny glass window with ease.

The two strands of the genetic material DNA, the molecule that encodes the information in your cells and all other cellular life, are held together to make the familiar double helix by links called *hydrogen bonds*. The forces involved in these links are just enough to hold the strands together and maintain the integrity of the molecule, but just weak enough that the two strands can be easily unzipped when the cell is dividing in two and the information in DNA must be copied. The replication of DNA and the architecture of its multiplication can be understood as the forces between atoms.

At higher levels of its hierarchy, biology still came to the fore. In explaining phase diagrams (graphs that show the state that matter adopts at given pressures, temperatures, and volumes), I found some illustrations from the world of biology useful. The fish that swim unmolested by predators and in the comparatively warm water trapped beneath the ice on a frozen wintry pond take advantage of the negative gradient of water's melting curve on a phase diagram. Put simply, when water is frozen, it becomes less dense and floats. Fish that remain active in the winter have evolved to cope with living in the habitat under ice—their behavioral evolution is constrained by some simple facts about the behavior of water that can be manifested in a phase diagram.

Even at the macroscopic scale, physics both explains biological systems and constrains their operation. When clarifying how large creatures travel through water, we are confronted with questions such as why fish lack propellers—what physical laws make a flexing body a better way to get through the ocean and away from a shark than a propeller, the solution of choice to human engineers? The behavior of fluids and the objects that travel through them provides extraordinarily tight constraints on the organisms that can evolve and the solutions they find to live within these constraints.

After teaching this course, I was surprised not by how we could find biological examples of physical laws in action, but by how deeply simple physical rules fashion and select features in life at all levels of its hierarchy, from an electron to an elephant. I was well aware of how physics can shape whole organisms, but I was awed by the sheer pervasiveness of the reach of physical principles, like tentacles, stretched through the entire fabric of life. And despite the inherent uncertainty swirling around subatomic particles in the quantum world— uncertainty that might reasonably make a cautious physicist wonder about how confidently we can bring biology and physics together—the shape and chemical composition of Schrödinger’s cat and the height of Werner Karl Heisenberg himself are highly predictable, convergent features of physical principles operating in biology.

Sometimes, scientists use the oceans as an analogy to evolution. Different animals represent islands of biological possibility, where solutions to successful adaptation to the environment are constrained by what is physically possible and what an organism already has on hand: its history. Between these islands, there are vast oceans of impossible solutions that life must navigate between to find new islands of possibility. Its seems extraordinary that life manages to home in on these islands and that living things seem to arrive at the same haven, like a party of separated shipwrecked seafarers that find themselves marooned on the same deserted outcrop in the middle of the Pacific Ocean. How is it that two animals, such as a bat and a bird, home in on the same functional solution to flight? This convergence cannot be easily explained by a common ancestor, since their ancestors lacked wings, a fact borne out by the very different wing anatomy in the two creatures. However, there is nothing uncanny about life's ability to land on the same solutions. Impossible solutions are impossible solutions, which means that the ocean of impossibility does not exist at all.

We might instead try to visualize the physical aspects of evolution as like a chessboard. Each square is a different environment, a different set of physical conditions to which life must adapt. When a living thing moves across the board, it automatically finds itself in another space to which it must adapt using a range of well-defined physical laws. For example, the laws of hydrodynamics that enforce certain forms in a fish would be replaced by the dominance of new rules when it crawls onto land. Limbs that allow movement against a more dominant influence of gravity and equations that determine the rate of evaporation as the midday sun mercilessly tries to desiccate our new denizen of the landmasses become some of the shapers of evolution. But there is no intermediate ocean of impossibilities. There are only physical principles seamlessly operating together in different combinations and magnitudes in different environments. Life moves from one environmental condition to another, those laws operating all the time to select successful conformists to physics, while the environment or competitors ruthlessly eliminate the forms whose adaptation to the unwavering requirements of these laws fails to allow them to reproduce.

There is a distinction worth making here. The ocean analogy works rather better when we think about how effectively creatures are adapted to their environment. In the extreme example, an insect born with a missing wing is likely to be severely handicapped in its ability to succeed in the evolutionary game. The idea of organisms occupying a vast landscape where islands and the peaks of mountains represent organisms best adapted to their environment and the plains and oceans between as the organisms less well adapted and less likely to succeed forms the basis of the concept of adaptive landscapes. However, there is nothing strange about life's ability to find similar evolutionary solutions to environmental challenges. There is no empty space to explore. Living things just move from one place to another; when the physical laws confront them, they must adapt to reproduce. If they do not, we never see them again. Those physical laws often demand similar solutions.

In this book, I do not expect the reader to be surprised that biology and physics are inseparable, that physics is life's silent commander. Instead, I intend to illustrate the wonderful simplicity of life from population to the atomic scale. I also suggest that these laws are so ingrained, from the atomic structure of life to the social behavior of ants, that life elsewhere across the universe, if it exists, will show similar characteristics.

Surely, though, we might say, "Life cannot just be about physical principles. What about the cheetah that chases the gazelle? Not merely a physical effect on the gazelle, but a true biological interaction." The cheetah that races across the African savanna to catch the hapless gazelle for its next meal is exerting a selection pressure on the gazelle, and this pressure is, at the level of the biological response, physical. The gazelle will survive this encounter if it can outpace the cheetah. Whether the gazelle can escape depends on how quickly it can release energy in its muscles or how deftly it can twist and turn as it seeks to evade the oncoming predator. This ability is itself a product, among other things, of the forces that the knees of the gazelle can endure and the torsion that its leg bones and muscles can accept as it seeks freedom. These factors ultimately are determined by the structure of muscles, bones, the acuity of eyesight, and so on. Either the gazelle will survive to get closer to reproductive age, or it will not. This selection pressure cares not that the cheetah is another biological entity. It could just as well be a fast-running robot built in a physics laboratory at the University of Edinburgh programmed to run across the savannas of Africa, randomly intersecting and killing gazelles. The only matter of importance is whether the biological, and ultimately physical, capabilities of the gazelle allow it to survive the cheetah and what adaptations in muscular properties, bone strength, and other factors allow its offspring to be the successful successors.

The points I make above apply equally to the evolutionary changes that occur in organisms not just from selection restrictions in the environment, such as predation, but also by new expansive opportunities provided, for example, by unexplored habitats and food resources. Many of these changes, both in the short term and ultimately in evolutionary terms, projected onto living things in their environment may be caused by fellow biological travelers on Earth. However, the adaptations required to ultimately survive or exploit the changes in the environment or other organisms are often tightly channeled by physical principles.

All these adaptations are, of course, bounded by the restrictions that may be imposed by the prior shape and form of the organism’s ancestors or in its developmental patterns. These historical architectures and limits in how living things can develop and grow are in themselves boundaries set up by previous evolutionary selection, and these boundaries merely constrain how an organism can respond to the full set of physical laws theoretically available to it and imposed on it. They narrow the field of play further.

There is a question that might be lurking in the mind of reader. You might be wondering, “But what *is* life?” After all, the preceding discussion has rather assumed we agree on what life is. The question of what defines life has occupied the minds of many good people for a long time. But for the purposes of this book, I do not need to advance that discussion. For simplicity’s sake, I take as implicit in this book a convenient working definition of life, which is essentially that living matter is material capable of reproducing and evolving, consistent with a definition made by biochemist Gerald Joyce, that life is a “self-sustaining chemical system capable of undergoing Darwinian evolution.” The capacity to evolve, that is, Darwinian evolution, is the feature of life that allows organisms to change over time and become better adapted to their environment. On a more easily understood level, on the Earth, this capacity includes almost all the familiar life forms, including the eukaryotes, the domain of life that embraces animals, plants, and many other organisms such as fungi and algae, and the prokaryotes, within which the bacteria and archaea (another branch of single-celled organisms) reside.

We could argue that the word *life* is merely a human categorization, something that will never yield to concrete definition. Life might just be an interesting subset of organic chemistry; it is a branch of chemistry that broadly deals with lumps of carbon compounds that happen to behave in complex ways. Its capacity for reproduction leads to evolution as environmental forces act on this reproducing material. Life’s apparent persistence on the planet is a product of the evolution of a genetic code within the reproducing material; this code allows for modification and variation in many reproduced units of that matter. Selection pressures act in different environments to whittle the variants down to the successful ones that are subsequently reproduced and distributed into new conditions.

However, whatever we decide about life, whatever the definition or concept we choose, any of these possibilities is entirely consistent with simple physical laws. In his engaging 1944 book, *What Is Life?*, Nobel Prize–winning Austrian physicist Erwin Schrödinger famously described life in physical terms as possessing the attribute of extracting "negative entropy" from the environment, a slightly unfortunate phrase as it has little formal meaning in physics. However, it was a phrase he chose to capture the idea that life seems as if it is working against entropy, which is the tendency for energy and matter to be dispersed and dissipated into thermodynamic equilibrium. Entropy is a basic attribute of matter and energy encapsulated by the second law of thermodynamics, which recognizes this tendency for things to achieve such an equilibrium. In many cases, this attribute equates to things becoming more disordered. In Schrödinger's view, life was in a struggle to fight entropy.

Life tends to create order in a universe ultimately prone to disorder. This attribute perplexed Schrödinger and has seemed mysterious to generations of thinkers. When a lion cub grows and eventually reproduces, all the new matter bound up in that adult lion and its offspring represents more ordered, less randomly dissipated energy than when the lion was a small cub nipping at its mother's heels. Indeed, for a long time, it was something of a challenge to biologists and physicists to explain why life seemed to be doing something apparently in violation of the laws of physics. However, when we look at life in another way, rather than viewing it as something anomalous and almost fighting the laws of physics, we can instead see it is a process that accelerates disorder in the universe—very much in line with physical processes that describe the cosmos. The best way to explain this idea is to use my lunch sandwiches.

If I place my sandwiches on a table, provided they are left alone, it will take a very long time for the energy in their molecules to be released. Indeed, the energy in the sandwich may not be released until it ends up in the Earth's crust from the movements of the continents during plate tectonics, the sandwich crashing down into the depths of the Earth, heated to great temperatures in the far future, when its sugars and fats will be broken down into carbon dioxide gas. However, if I eat the sandwiches, within about an hour or two, their contained energy will be released as heat in my body and some carbon dioxide exhaled in my breath, with some portion of it being used to build new molecules. In essence, I have accelerated, greatly, the dissipation of the sandwich into energy. I have enhanced the rate at which the second law of thermodynamics, which drives the universe toward disorder, has had its way with the sandwiches. Of course, if I leave my sandwiches on my table, they will go moldy and be eaten by bacteria and fungi that land on them—these organisms will have merely beaten me to it in dissipating the energy of the sandwich into the rest of the universe. Mathematical models show that this idea is not mere whimsy, but that the process of life and its tendency to grow, expand in population, and even adapt can be described by thermodynamic rules.

Living things show extraordinary local complexity and organization, but the process they are engaged in is accelerating the dissipation of energy and the rundown of the universe. Local complexity in organisms is an inevitable requirement to construct the biological machines necessary for this dissipative effect to occur. As the physical universe favors processes that more rapidly dissipate energy, then life is contributing to the processes resulting from the second law, not fighting it. At least, that is one way to view the phenomenon of life. Seen from this perspective, it is easier to understand why life is successful.

Ultimately, of course, when there is no more energy to dissipate or when environmental conditions become unsuitable for life as the oceans all boil away in the searing sky of a more luminous Sun a couple billion years from now, these local oases of complexity that once seemed to defy the second law will do so no more. They too will be destroyed.

This apparent detour relates to us simply because it underpins the idea that life is very much a physical process at work. Living things are collections of molecules behaving in a way that is consistent with, and encouraged by, the laws of physics. We would expect it to be elsewhere across the universe. Within this overarching behavior, the living things carrying out this process are themselves subject to the laws of physics. In these pages, I am less concerned with prolix and otiose deliberations on the definition of life and more interested in the universality of reproducing and evolving matter that we choose to call life.

The more we learn in physics, chemistry, and biology, the more we are confronted by the simplicity of rules that govern the universe and their unexceptional character. It has been something of a theme through the history of science that major paradigms have overturned the exceptionalist view of our place in the universe. The Earth as just one planet circling the Sun and the descent of humans from apes are two of the most traumatic conceptual changes to our worldview in the last few hundred years. These ideas replaced the geocentric view of the universe—the Earth at the center of our Solar System, populated by people very special and separate from the rest of the animals.

That biology conforms to physical laws raises fundamental questions about the wider universal view of biology: If life exists elsewhere in the universe, will it be like life on Earth? Is the structure and form of life unexceptional as well? At what level of organization could life elsewhere be the same? Is the choice of elements in the ladybug's leg the same in another galaxy? What about the molecules the atoms come together to form—would the molecules that build and shape the ladybug leg be the same? And what about the ladybug itself? Are there other ladybug-like creatures in another galaxy? Could it be that ladybugs, at all levels of architecture, are unique to Earth?

If physics and biology are tightly coupled, then life outside Earth, if such life exists, might be remarkably similar to life on Earth, and terrestrial life might be less an idiosyncrasy of one experiment in evolution, and more a template for much of life in the universe, if it exists elsewhere. Such an assertion would imply predictability, the hallmark of a good scientific theory.

A favored trope among science-fiction writers is to imagine any number of extraordinary life forms inhabiting other planets and to contend, therefore, that we are limited in our imaginations and, consequently, that we cannot make sensible predictions.

As early as 1894, in a *Saturday Review* article about alien life, science-fiction writer H. G. Wells reflected on earlier suggestions that silicates (the silicon-containing materials that make up rocks and minerals) might do interesting chemistry at high temperatures: "One is startled towards fantastic imaginings by such a suggestion: visions of silicon-aluminium organisms—why not silicon-aluminium men at once?—wandering through an atmosphere of gaseous sulphur, let us say, by the shores of a sea of liquid iron some thousand degrees or so above the temperature of a blast furnace."

He is not alone. In 1986, Roy Gallant wrote *Atlas of Our Universe*, a well-known exposition of the possibility of the limitless potentialities of life, for the National Geographic Society. The book contains a wonderful plenitude of imagined life forms in our Solar System. The Oucher-pouchers are large bags of gas that prance around on the surface of Venus and cry "ouch" every time they hit the surface, baking at 460°C. Their counterparts on Mars are the Water-Seekers, long, slender creatures like extended ostriches that sport vast furry ears with which they can enclose themselves in the cold Martian nights and winters. A giant carapace over their heads protects them from ultraviolet (UV) radiation, and with their long proboscises, they dig deep into the Martian subsurface to find water. The imagination reaches far beyond these two worlds. The Plutonian Zistles are intelligent ice cubes on Pluto (the National Aeronautics and Space Administration [NASA] New Horizon mission, perhaps glinting briefly overhead, presumably changed their culture for good), and the Stovebellies of Saturn's moon Titan combust material inside themselves to maintain warmth at a chilly -183°C. They propel themselves through Titan's hydrocarbon-rich atmosphere by the unedifying means of emitting bursts of gases from their rear ends.

None of Gallant's creatures have ever been observed, and that is an interesting fact. Assuming (and this is a big assumption) that life would emerge on other planets if the conditions were right, these novel biochemistries and creatures are, not insignificantly, absent in our Solar System —life forms that would have merely adapted to the different conditions found on those worlds. On most of these worlds, the conditions are so extreme that, according to our knowledge of the limits to life on Earth, we would predict that none of these planets and moons could today have complex multicellular life on their surfaces. That is what we observe. What we see on Venus, for instance, fits our predictions based on our knowledge of the boundaries of growth of terrestrial life—boundaries established by physical laws.

We do not yet have another example of life with which to test whether our biosphere is exceptional. Consequently, many observers might say that the question of whether life on Earth represents a universal norm can be nothing more than speculation, unbounded conjecture of the type that makes interesting conversation at the coffee table, but little more. However, this observation is inaccurate. The principles provided to us by physicists reveal the foundations of what is possible. Observations of the universe from astrophysicists can tell us about the preponderance of elements such as carbon and of molecules such as water; this information can yield insights into how common the chemical building blocks of life may be throughout the cosmos. From chemistry laboratories, our extensive knowledge about the reactive potential of elements in the periodic table and their ability to form complex structures can tell us about how universal the chemistry of life might be.

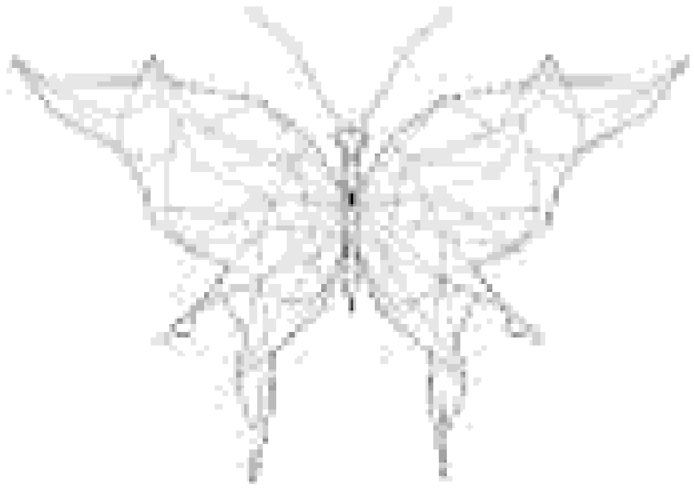
The biophysicists have much to tell us about molecules that have evolved independently in many organisms on Earth and allow us to question how universal the rules for doing chemical reactions in cells might be. The microbiologists' knowledge of life in extremes informs us about the physical boundaries of life and whether these are likely to be universal. From the paleontologists, we are given a vista across the life forms of the past. How similar or different are they from those alive today, and what might explain these observations? Planetary scientists collecting information about other worlds tell us whether, with their cameras and other instruments, they find conditions potentially supportive of life. We can compare the biological status of these worlds with our expectations.

From these disciplines, we can gather an abundance of information to build a hypothesis about the nature of life. In this book, in investigating the link between physics and life, I also explore the idea that life is universal at all levels of its hierarchy. By this, I do not necessarily mean identical. Ladybugs may not be the same on other worlds as on Earth, but the solutions used by living systems to proliferate on the surface of a planet might be broadly similar, from the way they use a subatomic particle, the electron, to gather energy right through to the behavior of their populations. We will know life if we eventually find it, and it will be recognizable as very akin to life on Earth.

It is apposite to give Charles Darwin the last word of the first chapter. In the finale of his *Origin of Species*, he summed up his feelings by declaring that he could see a certain grandeur in the evolutionary view of life. We might also remark that there is a beautiful simplicity. As physical laws, unyielding and unswerving, work their way through every form of life, extinct and extant, there is a breathtaking similarity in the products of evolution, a resemblance molded by the very laws that have shaped our universe for over thirteen billion years.

CHAPTER 2

ORGANIZING THE MULTITUDES



WHEN I WAS A boy of about eight, I was a typical daydreaming child. I would sit on the Victorian stonework, leaning against the black iron railings, and with my small magnifying glass, I would focus the rays of the sun on an oblivious ant going about its tasks. With my death ray, I would chase the little creature across the irregular pitted surface until I caught it in the glare and it spat and fizzled.

Ant chasing was an extracurricular activity at a typical English boarding school, and it was preferable to some of the others, including learning more Latin. I dare say it remains a macabre pastime for inquisitive, slightly destructive children to this day. In my juvenile unpleasantness to these innocent insects, I was party to their miniature world. I saw on many occasions the long, regular lines of ants tramping back and forth across the stones, some moving slowly, others fast, some with pieces of food, and a few with the carcasses of their fallen comrades. Every now and then, two of the scurrying forms would clamp heads as if exchanging instructions and then part, running off with hurried intent in opposite directions. What were they saying? The social activities of these ants fascinated me, and more often than not, I would prefer to just sit diligently and watch them.

But I saw something else. In my preadolescent activity, I witnessed the delicate nature of life. By merely taking the natural light from the sun and magnifying it just a few times, I could transform a living, intricate machine of organic matter into a blazing inferno. Life really was tenuous, poised at the boundary of physical extremes that, with a mere change in their magnitude, could define the difference between life and death. These creatures, like all of us, lived in a world at the mercy of hard physical limits.

Nevertheless, within these constraints, the ants went about their business. Watching them coalesce, exchange information, and organize could convince anyone that what was at work here was nothing short of social organization. A vast society of insects, merely on a scale smaller than us, worked toward their goal of constructing their nest and ensuring that they had enough food to perpetuate their colony. For many years, this top-down society was how it seemed to scientists. The queen ant, safely ensconced in a chamber within the nest, was further proof that this incredible collective effort was under the control of a monarch, a figurehead that directed and controlled the many instructions that must be needed to coordinate hundreds, thousands, and sometimes millions of ants toward a single, unambiguous task.

It is easy to see how this phenomenon led many to question how such a tiny thing, the queen ant, even at her often-bloated size, could possibly contain, let alone process the astonishing amount of information needed to operate the ant society. Ant civilization attracted the attentions of many biologists and animal behaviorists, such as American scientist E. O. Wilson, whose work from the 1970s on insect societies helped found the field of sociobiology.

A fascination with insect societies and the draw to understand what managed their multitudes caused a new group of scientists to become engaged with ant organization. Physicists, who are wont to avoid the dizzying complexities of things so unconstrained as ants, took an interest in the creatures. A collaboration emerged between biologists and physicists. They asked some different questions: Are these societies really so complex? Are they fashioned by flows of information and instructions beyond the realms of our computers? Are they under the whims and dictates of their queen, a leader we may never fully fathom?

What they found was remarkable.

Ant nests are complicated structures whose extent and detail can reach colossal proportions. A metropolis of nests containing an estimated three hundred million worker ants and a million queens was found on the coast of Hokkaidō, Japan, in 2000. Not a single nest, this labyrinthine construction of forty-five thousand nests was connected by shafts and tunnels and covered an area of over 2½ square kilometers. If such a city were to be built by humans on our own scale, we would require numerous architects musing, deliberating, and planning with someone who could oversee the whole project and could be relied on to keep the entire enterprise on track.

Yet among the ants, it seems, such vast empires can be constructed using the simplest rules.

Deep underground, an ant carefully and gently removes one soil grain at a time, dragging it away and dumping it to one side. Quietly and with seeming intent, it starts on a job too big for a single ant, so it releases some chemicals, pheromones, that attract a neighbor to help. Now two ants are busy working away, removing grains and starting the task of building a new chamber. They too need help, so they recruit two more ants, and those four ants recruit four more. Now there are eight. Quickly, we have what is known as a *positive feedback effect*, a near exponential growth in the number of ants now steadfastly dragging away grains of soil. At last, we have some significant effort and the chamber begins to grow at a sensible rate. Over minutes and hours, the new home takes shape.

But there is a problem: there are not an infinite number of ants available. Other chambers are being built, adding to the pressure for workers across the expanding empire. As the chamber grows, the ants working on it become more dispersed across its surface. The recruitment of ants slows down, and as it does so, a negative feedback sets in. Fewer ants mean reduced pheromone emissions and therefore still fewer ants. Building of the new chamber grinds to a halt. But no worry, because next door, another ant has started a new hole next to a tunnel full of ants. And so the process repeats: in little holes across the nest, brand-new chambers are formed. Now with all this fresh space available, the nest can accommodate more ants, so as the volume of the nest grows, the total population of the colony will also swell, keeping pace with the volume of the nest.

Take these simple ideas of positive and negative feedback effects between individual ants meeting and greeting each other in their fossorial wilderness, and write them into a computer program. Now you can recreate the chamber-building activity of ants and even predict the growth of the whole colony.

Remarkably, no architect is needed for this task, no grand designer to draw the ant nest on a board and to direct and supervise the workers on the job. Despite the overpowering wish to draw some sort of parallel between the impressive scale and collective effort these insects master and the building of the Egyptian pyramids, there could not be a bigger difference. The ant nest can be predicted with nothing more than simple rules operating between individual ants. The queen provides the focus of the nest, the source of eggs and new workers, but the everyday tasks of building the nest are the product of basic interactions between lots of busy ants.

The consequence of this order is that some of these antics can be written down in relatively straightforward equations. Often in the natural world, in physical, chemical, and biological systems, a *power law* explains the relationship between things. Put simply, it means that one item we might be measuring, such as the volume of an ant nest, changes in proportion (as a fixed power) to something else, perhaps the number of ants, with the simplest expression being:

$$y = kx^n$$

> where x is one thing we might measure (say, the volume of the nest), y is what we want to know (say, the number of ants), and n is the number (the power, hence, a power law) that scales the relationship between them (which can be measured). For example, for the ant species *Messor sancta*, the value of n is 0.752. The value k is another proportionality constant that can be worked out for any given process.

Power laws come about because of some inherent link between two things that are being measured, and often that link is rooted in a physical principle. For our ant example, the more ants there are, the more grains of sand or soil they can move. Since the collected three-dimensional grains essentially amount to the total volume of the chambers in the nest, it perhaps is not surprising that all other things being equal, the number of ants is related to the volume of nest they build.

Not confined to ants, power laws scatter through biology from the largest to the smallest scale. The laws appear in other places as well, since their ubiquity underscores the regularity in life. In quite different places, we find the same mathematical relationships. The laws of the ants are written in the same formula as other features of living things.

Perhaps best known among power laws is Kleiber's law, named for Max Kleiber, a Swiss-born physiologist. He measured the activity of a variety animals and found a simple relationship between the metabolic rate, essentially the energy the creature is burning, and its mass:

$$\text{Metabolic rate} = 70 \times \text{Mass}^{0.75}$$

This equation tells us that large animals have greater metabolic needs than do smaller ones. A cat has a metabolic rate about thirty times that of a mouse. This relationship makes sense, since a large animal has more mass to keep going. However, the power law also tells us that smaller animals have a higher metabolic rate for each part of their volume than do larger animals. Smaller creatures tend to have a higher proportion of "structure" such as muscles than fatty reserves than larger animals have. They also have a high surface area relative to their volume and so they will tend to lose heat more easily, burning up more calories per unit of weight than larger animals burn.

The exact physical underpinnings of Kleiber's law and many other so-called allometric power laws that relate the size, physiology, and even behavior of living things are becoming better understood. Their elevated status to "laws" would make many physicists wince. Most of these mathematical observations do not express some fundamental law like Newton's laws of motion; rather, they are general relationships. However, these intimate links, like many other power laws in biology, speak to us of the underlying order in the biological world, the interconnectedness, from populations of ants to the size and physiology of living things, that ultimately must conform to real physical laws. Many fixed relationships between the features of living things such as metabolic rate, life span, and size of animals that conform to power laws can be explained by the network-like properties of life.

Within the phenomenon of the ant chamber, there is a beautiful example of how complexity can emerge from populations of organisms with simple rules. Put many ants together that interact, and the to-and-fro of their exchanges will lead to patterns. At their core, the interactions are elementary, but mixed and matched, they lead to variegated behaviors.

Attempting to reduce the tangled complexity of populations of organisms, from ants to birds, to more tractable physical laws has fallen under the realm of a part of physics sometimes called *active matter*. This field strives to fathom how matter behaves when it is far from equilibrium, when it has not settled down into a stable and sometimes inactive state. For most of us, being "out of equilibrium" is synonymous with disorder and imbalance. Yet, physicists have found that when systems are far from being in a settled state, rather than disorder, ordered patterns sometimes emerge, and this order can drive biological processes.

In a landmark paper published in 1995, one early attempt to ignite the study of active matter, Tamás Vicsek at Eötvös Loránd University in Hungary developed a straightforward model of hypothetical particles bouncing around and occasionally meeting each other. He found that at low density, these virtual creatures, or blips of data, behaved randomly. Their concentration was just too small for anything noteworthy to happen. However, bring them together at high enough density, and now they move in a way that is influenced by the movements of their neighbors. Mutual interactions cause collective patterns and behavior to emerge. A shift, a phase transition, from one state to another dramatically occurs. These early beginnings in the field of active matter showed how grand things can happen from simple designs. A growing interest in self-organization in living and nonliving systems followed.

Biology is no doubt a special part of active matter. Living things have history, evolutionary quirks, behavioral specialisms even, that make them not mere particles bouncing off each other like atoms of a gas in a box, but more complex and, to some extent, unpredictable entities. Despite these idiosyncrasies, many features of the biological world at the scale of whole populations are successfully reduced to principles that are more transparent. From the swarming of bacteria to the flocking of birds, equations can be derived that help predict behaviors seen in the natural world. Vicsek's elegant paper hinted at the physical underpinnings of collections of entities in evolution's great experiment.

The feedback loops that direct the growing ant empire also decide how those same ants will get a meal. Outside our ant nest, a delicious juicy orange has just dropped from the branches of a tree. Within days, under the warmth of the sun, it begins to rot, oozing its sugary interior onto its surroundings. An ant, scouting around outside the nest, its antennae feverishly flicking, picks up the scent of the moribund fruit. It stumbles across this treasure trove and swings into action. Scurrying around the orange, it bumps into one of its fellow workers and, in a brief meeting of heads, instructs the other to return to the nest and recruit more workers. Soon, a trail is established to the nest, ants darting back and forth along the trail, great globs of sugary fluid in their mandibles. As each ant in the trail recruits others nearby, the numbers multiply rapidly and soon we have a miniature road crammed with them dashing back and forth.

As the ants smother the orange, no amount of extra workforce will be much use. Now there are too many cooks in the kitchen. Soon the orange, dismembered in the feasting mandibles of the colony, runs dry and thus the numbers of ants recruited to the orange declines. Other ants, ensuring that the nest does not rely on only one orange, react to "keep-away" messages. These black sheep of the colony, if you will, deliberately head off in new directions to find new food sources. Eventually, the orange is depleted and the trail dies away. In the appearance and disappearance of ant trails, we have no queen ant sitting in her chamber with a map, planning new excursions to find food, drawing lines on a grid, and instructing her minions to systematically scour each square for food. Instead, plain rules, beginning with a lone scout ant trekking across the home turf, lead to mathematical processes that end in food.

Like other aspects of the ant world, we can even write this entire scenario in an equation:

$$p_1 = (x_1 + k) \quad / \; [(x_1 + k) \quad + (x_2 + k) \quad]$$

> where p_1 is the probability that an ant will choose a particular trail to run down. The probability is predicted using x_1, which is the amount of attracting pheromone on that trail, which may just equate to the number of ants already on the trail. The variable x_2 is the amount of pheromone on an unmarked trail, which an ant might follow instead. The variable k is the attraction level of a pheromone on the unmarked trail, and   is a factor that takes into account the

> nonlinear behavior of ants, in essence some of their social complexities and behavior that vary from species to species. The higher the value of , the greater the probability that an ant will go down a trail even if the trail has only slightly more pheromone.

This is the equation of feeding ants. Here, in essence, we have an equation that predicts where ants like to go for food.

A human analogy to this whole episode is the arrival of a new artisan cheesecake shop in Edinburgh. Delicious new cheesecake, handmade at that, is a delight for city dwellers to offer at their summer luncheons. Delia accidently stumbles across the shop and buys some for her next gathering. Her guests are delighted, so she tells her friend Sophia. Now Delia and Sophia are both telling their friends, and soon, everyone is calling everyone else. There is a run on the cheesecake shop. It’s the place to go. A cheesecake feeding frenzy engulfs Edinburgh. Soon, however, there is no one left in Edinburgh to call. Everyone knows about the cheesecake shop. The number of people dropping in at Bruntsfield Cheesecakes, begins to plateau. But there is worse. Now cheesecake is no longer chic. Soufflé is the order of the day, and a new shop opened up on George Street that does some pretty nice stuff. Those in the know now call their friends to get ahead of the game. Avoiding the cheesecake shop in favor of the new trend, the shop’s clientele declines. As the shop cuts back on making cheesecake, this sets in motion an even smaller demand and the cheesecake shop is all but abandoned.

Delia and her cheesecake or soufflé preferences look like a complex social arrangement, but they follow simple rules. She and her friends have received no instructions from Edinburgh Council (or the queen herself) on whether to buy cheesecake or soufflé. In the ant world, without the real complication of the somewhat intricate social mores of humans, these simple feedback processes also drive the ants to switch from one food source to another.

The world is never as straightforward as a single orange. Perhaps several oranges have fallen from that tree. Faced with a tantalizing choice, even the smallest fluctuations in the number of ants running around could lead to one orange or another being chosen first. So predictability comes from the equations—we can define the rules that decide in principle which trail an ant will go down, but there is unpredictability in how the equation is manifested and the exact trail it will work its effects on. In the complex variations of the natural world, these small fluctuations play an immensely important role in shaping behavior, and no doubt they contribute to our sense that living things are inherently unpredictable, different from inanimate objects.

Other occasions cause the rules to be less easily discerned. A particularly large ant colony may have so many individuals that they simultaneously swarm many oranges, tearing them apart in a feeding frenzy. Under these conditions, our delicate feedback effects are all but gone to the wall. And, of course, the environment itself will mess up those nice, elegant equations. Put one of these oranges in a crack in the ground or under some particularly cumbersome vegetation, and the trails and feedback processes suddenly become motley and tortuous. Nevertheless, beneath these quirks, the equations of ants work their way.

The feedback systems operating in the nest might even help explain another enchanting and mysterious feature of animals: synchronicity. This quality appears not merely in ants, but also in termites, birds, and other animals. If ants are just communicating one to one with no overarching supervision, then why do we see mass organization, sudden bursts of nest building or food foraging interspersed with quiet times, synchronous behavior between many individuals?

What appears to look like good evidence for social organization at a high level may yet again reduce to some plain rules. Some of the synchronicity is thought to be caused by those feedback loops we saw in operation as the ants built their nest. A trigger from a few ants ripples through the colony as they communicate with one another. Add in some programmed tendencies, like a natural period of quiescence after a sudden bout of activity, a sort of rest period not uncommon in many animals, and distinctive patterns of behavior can quickly appear to engulf the whole population. These phenomena require no superintendent to coordinate and watch over them, but rather they emerge from the self-organizing behavior of populations in communication at the individual level.

In seeing our capacity to describe ant behavior using equations, we are tempted to think that this is the whole story. Of course, ants are not mere atoms of a gas. An ant is made up of a quarter of a million neurons, the cells that transmit electrical information in our brains and in the nervous systems of other animals, including the tiniest insects. Like a miniature computer, an ant is not a mere passive observer of the world around it, like a small atom of gas bouncing and colliding with other atoms. It has oddities of behavior, perhaps molded by the ant that fell on it early in the day or the number of ants it was with earlier. And alongside that behavior, new calculations are constantly being made. The number of ants it bumps into in a given time allows it to estimate the sum of other ants nearby and so modify its conduct. Even the concentration of carbon dioxide, the gas exhaled by other ants, provides a measure of the density of ants in any part of the nest, feeding into that mini calculating machine to make it redirect its action.

Proactively, ants can respond to many cues being sent their way and can initiate new behaviors that propagate through the swarm. The behaviors amplify those infinitesimal feedback loops and changes in the environment that a passive particle would ignore.

In some ways, this capacity of a living thing to respond to what is going on around it rather than merely acquiescing to perturbations in its world is a categorical difference between a living and non living entity. However, those reactions are still within the fold of the overarching physical principles at work. The reactions complicate the matter, but they do not put living things outside the realms of rules and principles within which they can operate—principles that we can, with enough experimental and theoretical effort, fathom.

This union between physics and biology operates beyond the imperium of insects. Far above the troglodyte lair of the ants, physicists have been attempting to unravel the mysteries of birds.

Since the ancients, humans have gazed with joy at the sight of geese gracefully winding their way across the sky in echelon or V formations, apparently coordinated and organized. Equally impressive and grander in scale are the murmurations of starlings. Sometimes thousands of birds, huddled together in a giant pulsating wave, sweep and dive in an evening sky. The self-organization of these masses attracted the attention of physicists in the 1990s; perhaps with some trepidation, the scientists launched into attempts to understand these phenomena, apparently some of the most complex in the natural world.

Hampering efforts to explain how birds organize themselves in such splendid displays was a lack of computer power to run simulations and the difficulty of getting real data. Tracking several thousand birds jostling and changing direction in three dimensions is no minor technical task. Yet advances in computer processing power, better cameras, and image-recognition software allowed people to collect some real information about bird flocking. Perhaps most surprisingly, computer gamers and filmmakers threw their efforts into the fray. Sometimes, help comes from unexpected places. Need a flock of birds in your film? You had better make them look realistic. As computer-generated sequences in blockbusters became more prevalent, so too arose the need to accurately portray birds, fish, migrating wildebeests, and a whole variety of Disney superstars. Hollywood met science.

At the core of these new attempts to simulate how birds flock are some basic assumptions about their behavior. We must establish some basal rules on how they operate. It is safe to assume that birds want to avoid collision as one condition of their behavior. Otherwise, flocking would be a bruising and messy business. They want to align their headings and stay grouped together. If they do not do that, the group will disperse, and we would quickly have individual birds heading off in random directions. We can get more complicated if we want to. We could assume that birds will try to match the speed of nearby birds, part of the strategy for staying grouped together.

Take these properties, and put them into a computer, and you can produce strikingly lifelike simulations of clusters of birds and other flying animals. So much so that the bat swarms in the film *Batman Returns* were generated using these simple algorithms.

The complexity and the subtlety of these models have been magnified in recent years with arguments and discussions over the details. Should the important rule be keeping a certain radius around each bird, or is it the number of individuals nearby that matters? How do you estimate and account for attraction and repulsion between birds, considering that they do not merely behave like particles that either collide or stay apart, but that they will avoid neighbors or try to get closer? Deciding on these sorts of intricate elements is no easy task, and the whole enterprise is made more difficult because we do not actually know what is going on in a bird's head. What calculations are really being made? A model may reproduce something realistic, but it is not based on how birds are thinking in the natural world. A scientist without a birdbrain is limited.

Like our ants, birds too are subjected to evolutionary pressures. They might want to minimize the energy they use, to conserve it for breeding. They might be in an area with a high density of predators intensifying the birds' tendency to swoop and veer to avoid being eaten. As darkness falls and their visual acuity drops, their behavior might change. And so on. Myriad environmental cues and selection pressures influence flocking. But similar to the situation with our ants, these influences seem to be just a veneer of complexity on the underlying rules that guide their patterns of behavior.

If you watch a flock of birds the way people observed ants, you can become easily convinced that one bird must be leading them. If that sort of group was a bunch of human hikers out on a ramble with no leader, chaos and misdirection would soon ensue. Just as we do for insect communities, we project the structure of our own societies onto birds and assume that the apparently organized behavior of a mass of them must require an avian superintendent to guide the flock. It feels counterintuitive to think that such organization could happen without an organizer, that disintegration of the regularity of the flock must surely occur if there is no oversight. Yet rules applied to particles in a computer show that self-organization can emerge to produce the phenomenal complexity of flocking behaviors with no head bird.

The gulf between biological behaviors and our ability to present them in physical principles, in equations, is narrowing. The infant state of our true knowledge of self-organization does not lessen the quite impressive strides made in using equations to produce realistic simulations of animal flocking, bringing us to the world of computergenerated starling murmurations. As those models are refined, no doubt the accuracy will improve and the collaboration between physics and biology will deepen as their common ground is found in one of the most ambitious programs between the two fields—to predict the behavior of populations of living things.

There is one aspect of all this that we have ignored so far. It is something physics is less able to predict, but it is singularly important in understanding why those equations work. The principles that govern flocking birds do not tell us why they do it in the first place. If you watch a vast display of starling murmurations, you are immediately enticed by the question of why. An obvious idea is that they are avoiding predators, the classic notion of safety in numbers. Faced with thousands of birds, the predator, perhaps a hungry hawk, must select one, and with such large numbers, an individual's chances of being picked off are minimal.

The problem, as keen ornithologists soon recognized, is that the birds seem to flock at the same time and place every day. Their displays often last for over thirty minutes before they settle down to roost for the night. Surely, after a few days, rather than throw off predators, this regularity would attract predators, which would quickly learn that several thousand potential meals take to the sky each evening at a particular place. Quite apart from that, the flocking behavior —every evening—seems remarkably wasteful of energy.

There is another important thing for a bird to think about other than whether it is about to be eaten. The number of birds in a flock will affect the number of available roosting