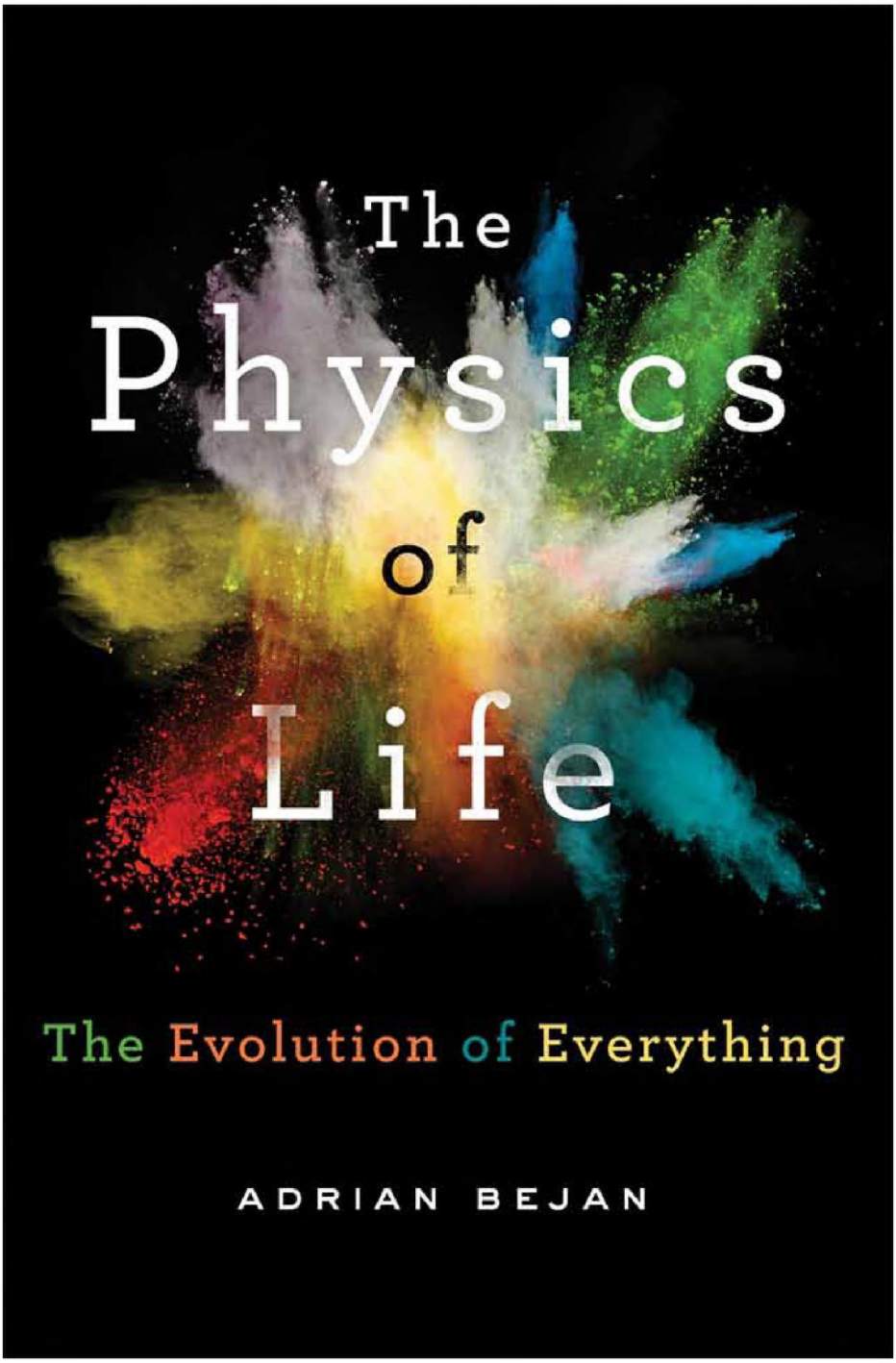

The Physics of Life

The Evolution of Everything

ADRIAN BEJAN

St. Martin's Press
New York

www.stmartins.com

Design by Letra Libre, Inc.

Library of Congress Cataloging-in-Publication Data

Names: Bejan, Adrian, 1948– author.

Title: The physics of life : the evolution of everything / Adrian Bejan.

Description: New York City : St. Martins Press, [2016]

Identifiers: LCCN 2015035874| ISBN 9781250078827 (hardcover) | ISBN 9781466891340 (e-book)

Subjects: LCSH: Evolution (Biology)—Philosophy. | Physics.

Classification: LCC QH360.5 .B45 2016 | DDC 576.8—dc23

LC record available at http://lccn.loc.gov/2015035874

Our books may be purchased in bulk for promotional, educational, or business use. Please contact your local bookseller or the Macmillan Corporate and Premium Sales Department at 1-800-221-7945, extension 5442, or by e-mail at MacmillanSpecialMarkets@macmillan.com.

First Edition: May 2016

10 9 8 7 6 5 4 3 2 1

Contents

Preface

To live or not to live, that is not even a question. Life is a universal tendency in nature. It is physical movement with the freedom to change. Every moving, flowing and hurtling thing exhibits the tendency to move more easily and to keep moving by changing its configuration, path and rhythm. This evolutionary flow organization and its end (death) are nature, the animate and inanimate realms together.

The question is, what is life, as physics? Why do life, death and evolution happen?

In this book, I answer this question. In fact, had I not known the answer I would not have been able to formulate the question about what life is. In short, everything that happens by itself, everywhere and every time, is nature (or physics, from the Greek). Through our tiny lens as mortals, this means that everything obeys the laws of physics. By this I mean primarily the laws of physics that we all learn in middle school and high school, which have made sense to most people for generations.

In nature nothing moves unless it is driven, forced, pushed or pulled. The power behind this movement is generated by billions of natural "engines" that consume "fuel" in many forms, such as food for animals, gasoline for our vehicles, solar heating for atmospheric

and oceanic circulation and the flow of water around the globe. The generated movement destroys its power instantly—it dissipates it in "brakes"—while penetrating and displacing its ambient, which resists the movement. Engines and brakes are two natural phenomena as old as the earth itself.

The phenomenon of life and evolution is how power production and dissipation conspire to facilitate all movement on earth, animate and inanimate, river, wind, animal, human and machine. This is a distinct phenomenon and a first principle of physics, and it is called the constructal law.

To place the life question in terms of physics is to inject physics into the descriptive narrative of life inherited from Darwin. In that narrative the subject of physics is missing. To see why this injection is needed, consider some examples of things that move and spread over an area (animals, plagues, river basins, extraction of minerals and news). How they spread follows the well-known S-curve phenomenon: over time it increases slowly, then faster and finally slowly again. The existing models describe this phenomenon as competition, the fight for survival and resources, reproduction rate, territoriality, chance and so on. According to what law of physics? Indeed, what fight for survival, resources and reproduction can be seen in spreading designs such as the river delta, the ice volume of the snowflake or the number of citations of a scientific publication?

Viewed from physics, the phenomenon of life and evolution at first seems counterintuitive. Instead of doom and gloom about the future of life on earth, the constructal law of physics offers a much more optimistic point of view. It's why I have written this book. Here are a few examples:

The world is not running out of energy and water. There is plenty of solar heating falling on the Sahara, and plenty of rainfall in the Congo. What the world needs in order to keep moving (to live, that is, to reach "sustainability") is the *flow* of useful energy (power) and

drinkable water throughout the space inhabited by humans. This means power plants of all kinds (more engines) for territories still without electricity, and desalinated water for huge swaths of land in arid regions.

No group is going to cut back on fuel consumption, because nobody prefers poverty over wealth, or death over life. Arguing against impact on the environment is arguing against movement, against life itself.

Fuel consumption will continue to be hierarchical. The reason is that the movements that emerge naturally, from the river basin to global air traffic, are hierarchical, with few large and many small movers flowing together.

The evolution of anything that moves on earth, including human movement, leads to hierarchy in movement, naturally. The world is an exquisite fabric of superimposed "river basins" of flows that distinguish themselves through their hierarchy. Few large channels flow together with many small channels, and they depend on and mutually benefit each other in order to move effectively and with lasting power.

Two ways to flow, fast and slow, are much better than one. The fast are the few large, and the slow are the many small. This is the way to serve with flow an entire area or volume. We see this hierarchy occurring naturally everywhere, from traffic in the city, to oxygen transport in the lung and fast and slow thinking in the flow architecture of the brain.

The world is not getting out of control. Why? Because every spreading flow on a finite area is destined to have an S-shaped history of growth. Young flows spread slowly. Adolescent flows spread faster. Mature flows spread slowly. There is no such thing as the "exponential" or "explosive" growth of anything.

Complexity in this world is not racing upward, out of control. Complexity is modest, steady and predictable, like the 23 levels of branching in the air tubes of the human lung. Sure, a larger lung or a

larger river basin is more complex because it is naturally hierarchical in a larger space. The traffic flow in New York City is more complex than in Durham. Neither is exploding in complexity, because if it did, the flow through it would die, at all scales.

Size makes for speed, longer life span and efficiency. We see this in everything that moves: animals, airplanes, rivers, atmospheric jets, rolling stones and whirls of turbulence. We witness this evolution in all sorts of technologies and athletics. For example, commercial aircraft have evolved predictably to look like the birds: heavier engines and fuel loads on heavier airplanes, wingspan equal to fuselage length, larger fuel load, longer range and longer flight time for larger flying bodies.

In athletics, the 100-meter sprint today is dominated by tall runners who take a few big steps to the finish line. Usain Bolt and the hippopotamus have comparable speeds because they have comparable heights. Yet, size is not the only evolutionary trend. In short-distance running, in addition to size, a high stride frequency is also an advantage. In long-distance running, the opposite evolutionary trend (toward smaller size) is the evolutionary path to winning. These contradictory trends are all predictable, from a physics point of view.

Cities will continue to grow, by natural design, not randomly. The design features (time, place and size) are now predictable because of the physics principle: few large streets allocated to many small streets, throughways and beltways. Cities happen, like all the other designs that humans unfold unwittingly because they facilitate human life: fire, power, speech, writing, science, rule of law, money, communications and sustainability.

Good ideas spread far, and keep on spreading. This evolving flow of design is what "good" means. The physical measure of a good idea is the increase in human movement that is created in one place by the physical implementation of the idea—the flow design change, the evolution in that place, at that time.

Knowledge, as physics, is ideas *and* action, the better design *change* that is put to use. What works is kept. This is why good changes spread naturally. This is what evolution is, and why it never ends.

* * *

Life and evolution are physics. They are an immensely broader and more important phenomenon on earth than what we learn in biology. The most useful science, like Newton's second law of motion and the laws of thermodynamics, is the science that covers any imaginable situation, irrefutably. Such is the physics of life and evolution.

I am sure you already know this aspect of physics, perhaps by other names such as self-organization, self-optimization, natural selection, self-lubrication, emergence and many more. I am even more sure that you did not realize the universal validity of what you know. The self, the natural and the emerging are one distinct phenomenon and a first principle of physics, now summarized as the constructal law.

I encourage you, the reader, to speak and write about your own mental images that complete the tableau painted in this book.

Adrian Bejan
March 2016

1

The Life Question

What is life? is, of course, the big question. In 1944, Erwin Schrödinger, the Nobel Prize–winning Austrian physicist, made a valiant and now classic attempt to answer this in his aptly titled book *What Is Life?*, which took up the question from a genetics and biology of living cells starting point. It is a perplexing and perennial question that has possessed philosophers and scientists from time immemorial. Just a few months ago we were informed in *The New York Times,* no less, by the science writer Ferris Jabr, that science has no answer to this basic question. "What is life? Science cannot tell us . . . scientists have struggled and failed to produce a precise, universally accepted definition of life." He adds that "nothing is truly alive." Naturally, I disagree with this.

This book is my attempt to explore the roots of the life question by examining the deepest urges and properties of all the things that move and that, while moving, change freely. This is nature and it covers the board, from the inanimate (rivers) to the animate (animals, humans, social organization). These urges were with us long before science emerged: the urge to live longer, to have food, warmth, power,

movement and free access to other people and surroundings. I will explore why all these things are "urges," why they happen by themselves, naturally, and why they are in each of us and in everything else that moves and morphs freely.

The urge for life, the life question (and its opposite, the death question, which we tend to avoid), is what this book is about. Unlike Schrödinger, however, I will place this question firmly within the realm of physics—the science of everything.

In my book *Design in Nature* (2012)[1] I wrote about the phenomenon of organization in nature and its physics principle, for which I coined the term "the constructal law" in 1996.[2] According to constructal law, life is movement that evolves freely, in both animate and inanimate spheres. Alive are all the freely changing flow configurations and rhythms that facilitate flow and offer greater access to movement. When movement stops, life ends. When movement does not have the freedom to change and find greater access, life ends.

In constructal law the life phenomenon is everywhere. Life unites the inanimate realm (rivers, lightning, snowflakes, air turbulence) with the animate realm (animals, vegetation, society and technology). Seen in this broad light, the life phenomenon is older than the biosphere, because the inanimate flow systems of geophysics populated the earth before the animate flow systems of biology.

Life, organization and evolution are physics (natural things, *physika,* in Greek), and are governed by their own law of physics.[3] I know firsthand the difficulty that the science-educated face when reading that life is a phenomenon of physics, comprising all the flow systems—inanimate, animate and human-made—that morph freely and evolve toward greater access. After all, the word "biology" means the study of life (*bios,* in Greek). Even a child knows the difference between animal movement and the rest of the moving world (rivers, winds, oceanic currents, volcanos, snow, rain, lightning and earthquakes).

The physics, the natural tendencies of all these moving things, are one. While in the 1800s the child associated the cart with the animate horse, the child of today associates the cart with the inanimate gasoline, engine and the money paid by the parent at the gas pump. After reading this book, the child of tomorrow will put the money together with the gasoline, the horse and the oats that fuel the horse.

This is how knowledge evolves—from science, technology and the rule of law it becomes, in one word, culture. What was obvious and understood piecemeal becomes one entity, much bigger and simpler. With every new generation, the child grows into a more knowledgeable parent and teacher, while increasingly ignorant of the tentative and disunited past. Knowledge is contagious, and it spreads naturally. I do not see a difference between art and science. They are both about images in motion. The inner pleasure is the same whether making a piece of art that inspires the viewer or coming up with a scientific idea that triggers explosions of images in the mind of the same viewer. Scientists and artists are specimens of the same species.

Freely morphing movement is a macroscopic phenomenon. The entity that moves does so relative to the rest—its environment—which does not move. Movement is contrast, and contrast is visible. We, the observers, call this phenomenon by many names—organization, configuration, design, architecture, change, evolution—names that make sense in our minds because they are as old and as frequent as the images that bombard our senses. Interesting as they may be, the unseen molecules, atoms and subatomic particles are not the macroscopic life phenomenon of evolving organization. Descriptions of their random walk, disorder and Brownian motion are not the same as descriptions of the paths of rivers, pulmonary air and city and air traffic.

In *The Physics of Life,* I move beyond the parameters of *Design in Nature.* I construct an edifice of examples to help readers understand the significance of the life principle in their own lives and in our culture today. These examples come from both the geophysical and the

animal realms, from the old and the new. They come together not as apples and oranges but as one, because the life phenomenon in nature is one. I will show how the constructal law informs the evolutionary designs that sustain life: power generation and use, transportation, technology and evolution; the spreading of new ideas, devices, knowledge, wealth and better government.

As I was finishing *Design in Nature* one of the most interesting discoveries for me (and what sparked the idea for *The Physics of Life*)

Figure 1.1 The world map of human air mass transit. Top: Where aircraft flew in 1992 (very lightly traveled paths not shown; adapted with permission from Springer: K. Gierens, R. Sausen and U. Schumann, "A Diagnostic Study of the Global Distribution of Contrails, Part 2: Future Air Traffic Scenarios," Theoretical and Applied Climatology *63 [1999]: 1-9); Bottom: The world map of human air mass transit today (with permission from the European Space Agency, "Proba-V Detecting Aircraft," January 5, 2015, © ESA/DLR/SES).*

was that air mass transit on the globe has a sharply hierarchical geography (figure 1.1). Even though air traffic connects the entire populated area of the globe (like the cortex of the brain), most of the air traffic is positioned over the North Atlantic.

Human movement has geography and history. It creates, like all the river basins put together, a constantly changing world map with a few large channels and many small channels. It has hierarchy. Because I cannot forget my MIT education, I thought of this in terms of physics. Seeing as how air traffic happens because it is driven by engines that consume fuel—*et voilà!*—the burning of fuel must also be hierarchical, with a world map of its own. A few large consumers of fuel collaborate with many more small consumers to spread the flow of movement throughout the entire population, all over the globe. The hierarchy of the whole is good for every moving individual.

Have money, will travel. In a flash, it became obvious to me that the geography of air mass transit and fuel consumption illustrates the geography of global advancement. The two legs of the air bridge over the North Atlantic are planted firmly (and historically) in the most advanced regions of the world, Western Europe and North America. This is how I decided to plot, country by country, the annual rate of fuel consumption versus economic advancement (measured as the annual gross domestic product, GDP).

What came out on paper is shown in figure 1.2. There is an amazingly sharp proportionality between fuel consumption and "wealth." Fuel consumption is physical (tangible, one can weigh fuel and measure the power associated with burning it), while wealth and all the other "obvious" notions used in economics (utility, the idea of money, being better off) are intangible. Economics, it appears, is physics as well; it encompasses the tangible and the intangible.

This led me to further discoveries. The fuel consumed annually in one country drives much more than the airplanes that carry the flying population of that country. The consumed fuel drives everything that

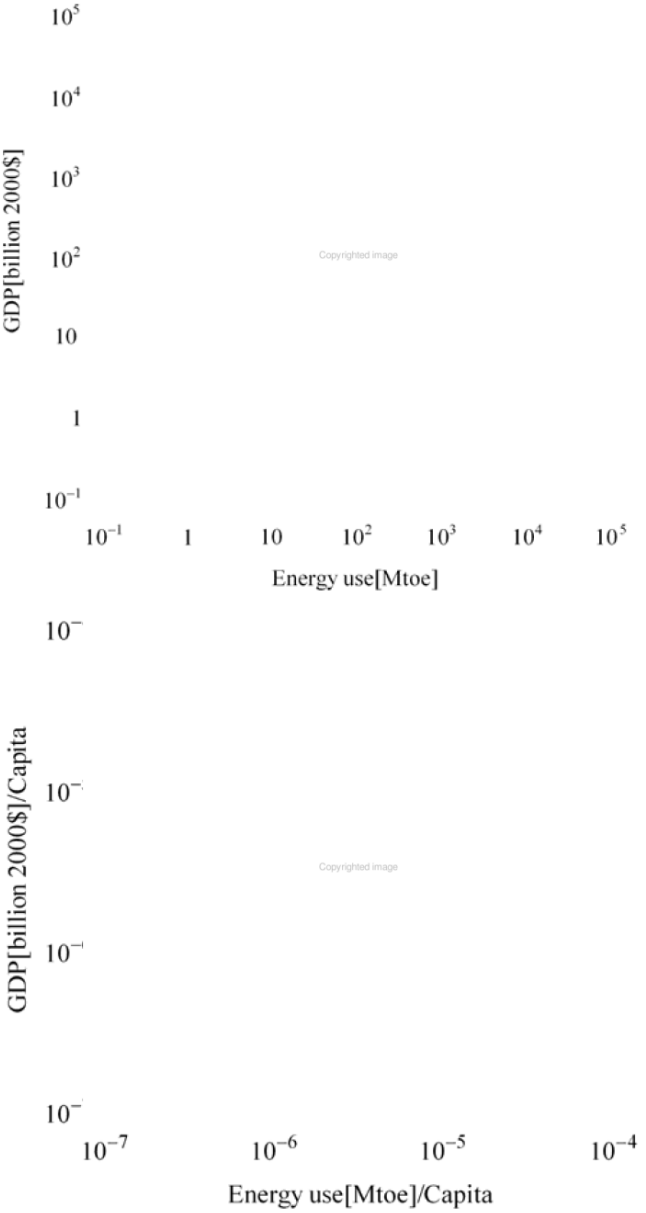

Figure 1.2 Wealth is movement. Economic activity means that fuel is being consumed for human use: the GDP (gross domestic product) of regions and countries all over the globe versus their annual consumption of fuel are shown above. The data are from the International Energy Agency, Key World Energy Statistics, *2006.*

moves, kicks, heats and cools. It drives the entire society. It keeps it alive. It sustains it. Why do I say "everything that moves"? Because the measure of wealth (GDP)—so sharply synonymous with the rate of fuel consumption—accounts for everything that lives, moves and changes in society.

While I was drawing figure 1.2, unusual answers to old puzzles started to voice themselves in my mind. For example, why are all the countries racing upward, along the same line? Why is the United States leading the peloton? Americans are not smarter than the people of other countries; in fact, most Americans are descendants of those people. Why is the urge to have "wealth" in every individual and group?

The answers boil down to the single fact that the urge for more and easier movement is in everybody and in everything that moves and changes, with freedom to change. In figure 1.2, this means that the dots must speed-walk to the right, toward more fuel consumption, not less. No one will cut back on fuel consumption, because no one prefers poverty over wealth, or death over life.

This is how the story of *The Physics of Life* got started. This voice in my mind, the relationship between GDP and fuel consumption, led me to question views that scientists, pundits, politicians and the public consider obvious. It allowed me to bring all the answers under a single scientific umbrella.

There is a hidden truth in science, and it is unveiled in this book. Science is interesting when it is about us, and when it is useful to us. This is why the ideas in this book are about our needs and how to achieve them, and how to construct a better future for humanity.

The story of *The Physics of Life* is rooted in the obvious: every animal and human wants power. We see this very clearly in the urge to eat—to consume—and in the march upward to the right in figure 1.2—food for animals, and fuel for our vehicles and machines. Food for the *human & machine species* (see chapter 4) is power, which

in physics is called *useful energy* (or "exergy") consumed, per unit of time. From power comes movement: body movement, internal flow (pumping blood and air), external flow (locomotion, migration, transportation). And from power we get the means to ensure our safety and comfort—warmth, drinkable water, health and the construction of highways and steel beams that do not break when we walk or drive on them.

My use of the word "machine" in the name of the human & machine species needs some explaining. It is not about automobiles, power plants, refrigerators and manufacturing. Machine is used in accord with its oldest meaning, which is contrivance (*mihaní* in old Greek), a sophisticated tool that allows for more effective use of human effort. Every artifact that we attach to ourselves is a contrivance, the shirt, the harvested food and the power drawn from an animal or an electric outlet. It's true that through the centuries new contrivances have made us much more powerful, bigger and longer living. Yet, a machine should not be confused with or limited to the biggest contrivances that empower us today.

The machine was in us from the beginning. It was also there from the beginning of science as mechanics and mechanisms, which are as old as geometry. The word itself belongs in the realm of physics because it is physical, the palpable and measureable version of our last name, *sapiens* (wise, or knowing). Words have meaning, especially in science.

The growth and spread of civilization on the globe is the flow of more power to more individuals, for greater movement of the whole. This is better known as the evolution of power generation and consumption (from domesticated animals, to slaves, serfs, windmills, waterwheels, steam engines) and the contagiousness of life (individual liberty, health, emancipation, affluence and empowerment). We cannot have enough of any of these design changes. They are good, and they stick because they are useful for our movement. This is evolution and life, as physics.

Everyone wants more power, not less, and everybody collaborates with others in order to get more. Collaboration itself is movement, because the root term "labor" means work, and work entails movement (work = force × travel). Collaboration is another word for organization, a flow configuration with purpose and the freedom to change, which together mean life. When the flowing entities are free to change, they turn to the right, and then to the left, and to the right again, to find better ways of flowing. Flow itself enables better flow over time. This is sustainability, as physics.

Life, as a concept in thermodynamics, is unambiguous and easy to grasp. It is the antonym of death. The thermodynamic definition of the dead state is well-established. It is the condition—the being—of a system (an amount of material, or a region in space) that is in complete equilibrium with its environment. For example, in the dead state the pressure and temperature of the system are identical to the pressure and temperature of its surroundings. Dead state means "nothing moves," not the system, and not its innards.

The opposite of the dead state, which I now define, is the live state. The live-state system is not in equilibrium with its environment. Differences of temperature and pressure (and other properties) are everywhere, inside the system and outside, between the system and its surroundings. As a consequence, the system is being pushed and pulled, heated and cooled, it is inhabited by flows (currents) and, above all, by organization. It moves as a whole and it morphs freely as it moves and flows.

The live system has flow, organization, freedom to change and evolution. Once present, these features distinguish the alive from the dead.

Life is movement, and in order for both to happen, movement requires work spent, work requires food and food comes from work—a job for the human, fighting and hunting for the carnivorous animal and constant walking and grazing for the herbivore. All these words

come together to say that life is work. This is the naked physics of life, but why is it important? It is important in education, which is my profession, where many of my contemporaries teach the young that there is a lot more to life than work. It may already feel this way to the child of ready money in an affluent society, where food is much easier to find than in other parts of the globe. The big picture, however, is that of a global movement of humanity that, in order to keep moving, must consume food and other streams (heating, cooling, freshwater) that flow from nowhere except work (power) spent.

To each of us, life is a private movie, a strictly personal show in which the individual is screenwriter, director, producer, actor, spectator and reviewer. The individual improves the plot as the tape rolls forward. The direction of the movie plot and the rolling of the tape are the same in all such movies, which is toward a longer movie.

This movie has a beginning and an end. There was nothing to watch before the beginning, and there will be nothing to watch after the end. For some of us, the movie script includes one or more intermissions, which cover the brief periods of unconsciousness that accompany modern surgery. These intermissions resemble what was before the movie started, and what will be after the movie ends. In view of all this, there are only two things to do: improve the script, and enjoy the show.

We are wedded to an incorrect, dichotomous understanding of life: natural vs artificial, animate vs inanimate, bio vs non-bio and nature vs nurture. Yet most of us are unaware that we are flowing together with so many like us. We are like the raindrops falling on the plain. The water must return to the air, and it manages to do so by flowing through many designs such as tree-shaped river basins, grazing and migrating animals, grasses, trees and forests, waves on the ocean, sand dunes, oceanic and atmospheric currents and disruptions caused by fallen trees and broken branches, all causing eddies, whirls and turbulence, all flowing and dying downstream. All this is life.

Symbiosis, the urge to live together when such association is of mutual advantage, is a manifestation of the life law of physics everywhere, bio and non-bio. We see it in two rivulets that come together into one stream. We see it in the fungi on the roots of plants, the mycorrhizal networks and the flow and life of the soil. We see it in every instance of social organization, where the urge to join is of selfish origin.

It is not that getting together and making one big thing out of a huge number of small things is the best arrangement. There is a balance to be reached between the large and the small, between the few and the many. Big is not the answer. The answer is that it is easier to move stuff on the landscape (animate, inanimate, social) with the support of a special tapestry of a few large and many small carriers. This balance, or hierarchy, is predictable in every domain we have looked at. This is how the flow most easily covers the available area or volume.

Organization (design) happens naturally. The word "organization" speaks of the fact that the design—the organ—is alive, with flows inside and around it, all belonging to a greater whole, and all morphing, evolving, growing, shrinking and moving in the world. Collaboration is a design that comes from the selfish urge of each individual to move more easily. We collaborate in order to flow together in ways that serve us better individually. These collaborations are channels through which things flow, channels that hug the flow and morph with the flow. They are not "links," and "networks," not strings tied between two or more nails.

Growth is not evolution. Both words refer to architectures that morph and flow, and both are predictable by invoking the laws of physics. Yet, they are two distinct phenomena. Growth is a phenomenon that occurs on a time scale that is much shorter and more special (limited, local) than evolution, which in nature is as old and universal as big history. Coming from the law of physics, my colleagues and I have shown that growth is the S-curve phenomenon of slow growth

followed by fast growth and, finally, by slow growth and no growth. The river delta growing in the Kalahari Desert, the cancer tumor, the animal body growing from birth to adulthood and the ice volume of the snowflake all fill a space the size of which increases in time unevenly, slow-fast-slow, en route to no growth (at the upper end of the S, the plateau). The time scale of the growth of the Okavango River Delta into the desert is the few months of the rainy season upstream in Angola. On the other hand, the time scale of the evolution of the delta is immensely longer, as its evolutionary design is the architecture of channels carved spring after spring after spring into the floor of the desert.

The Physics of Life explores how freedom is the most basic and most overlooked property of nature, and of thermodynamics for that matter. Every natural entity has freedom to change. Freedom means the ability of a flow configuration to change, morph, evolve, spread and retreat. This is the property that makes natural organization possible. Without freedom to change, organization and evolution cannot happen. Social organization, civilization and culture are the best-known evolutionary phenomena that illustrate this natural tendency to change freely, to evolve. To improve a design while loading it with constraints disguised as good ideas is nonsense. In this book I put these debates aside, and I focus on the physics, the root of the phenomenon.

The Physics of Life explores the evolution of technology as a phenomenon of natural organization, which is no different than animal evolution, river basin evolution or science evolution. The vehicle consumes fuel and moves on the world map. The vehicle and its movement are an evolving design. For example, new models of airplanes are larger (figure 1.3), fewer, and more efficient movers of weight, the same phenomena we see in animal evolution.[4] The vehicle is an assembly of many components (organs), connected and flowing together. I will show that the fuel that must be spent because of one organ is proportional to the weight of that organ. Likewise, the total amount

of fuel required by the whole vehicle is proportional to the weight of the vehicle, which is the weight of all the organs.

Any flow system is destined to remain imperfect, and yet it constantly morphs to flow better and more easily as a whole. In this evolutionary direction, its imperfection (the internal flow resistances) is spread more and more uniformly, so that more and more of the flow compartments are "stressed" as much as the most stressed compartments. The purposeful spreading of imperfection has no end. It will never be uniform. Evolution never ends.

The more we think of flow systems in this way, the more they look and function like animals. The design and movement of animals has been a puzzle. From the mouse and the salamander to the crocodile and the whale, animals are correlated by surprisingly accurate formulas (power laws) relating animal body size to flow and performance

Figure 1.3 The evolution of the major airplane models during the 100-year history of commercial aviation (A. Bejan, J. D. Charles and S. Lorente, "The Evolution of Airplanes," Journal of Applied Physics *116 [2014]: 044901).*

parameters. The way to see the law of physics of living systems is to see them as flow systems in motion, driven by power, with finite-size constraints and, above all, with freedom to change and time direction for the evolution of design changes.

In the design of anything from animal to vehicle, the flow has to be maintained. Life is movement. Everything needs to be kept alive by flowing, from rivers to walking and running, and to physical dexterity and reflex.

This discovery holds equally for animals, and explains why size is so important, throughout nature: big organs on big animals, small organs on small animals. Size is not a given. Size is a resulting feature of the evolutionary design. Size is predictable, deducible. The whole animal is a vehicle for moving animal weight horizontally on a landscape. The whole is a construct of organs, and each organ is "imperfect" if examined in isolation. The whole evolves toward becoming a better organization of imperfect organs. The whole is alive and evolving.

Diversity and hierarchy are necessary features of this natural flow organization. The large are few, and the small are many. Hierarchy is not inequality. Hierarchy is consistent with freedom. It is part of the natural design, and it is predictable. The food chain and the freight system are better-known versions of this natural organization. Hierarchy unites power producers and users, allocated to areas in a vascular design that covers the globe. The inhabitants of an advanced country move more weight over longer distances, through bigger channels. The entire economic activity of a country is this movement.

This book is about evolution as a phenomenon of all physics, animate and inanimate, all moving and morphing freely. In particular, it applies the idea of evolution to non-bio systems. One of the wonderful things about technology (for scientists) is that evolution is visible for everyone to see. The miniaturization of packages of electronics is one such phenomenon. This urge comes from each of us, to move

our bodies, vehicles and belongings more easily, and for a longer time and a greater space. There is no "revolution" toward smaller components. There is relentless evolution, and we see it in every domain, not just technology. Just think of writing, from antiquity to our day: clay tablets, slate and chiseled stone were followed by materials that allowed for a denser written content, by (in order) papyruses, parchments, books, mass printing and software.

Sports is another area in which we see evolution. Sports are obvious, so obvious that most of us are unaware of their scientific significance. The subtle aspect is the role that sports evolution plays in illustrating the phenomenon of life in nature. I show how to predict the future of sports, for example, why the fastest runners and swimmers are turning out to be bigger (taller), and how this trend will continue because of physics. I also explain the "divergent evolution" of running: short-distance runners (sprinters) are becoming bigger, and long-distance runners are becoming smaller. In team sports involving a throwing motion, such as baseball, the recorded evolution has been toward taller players, and the distribution of player heights on the field has evolved in accord with the need to throw fast.

The size effect is at the core of the design of life, and it is everywhere, not just in airplanes, electronics and athletes. The bigger are faster everywhere: animals, vehicles, rivers, winds and oceanic currents. The bigger are more efficient vehicles for moving weight. Bigger animals also live longer and travel farther during their lifetimes. Bigger stones roll farther, and their movement lasts longer. Bigger waves do the same. We will also learn why not every moving thing evolves toward being the biggest, and why natural organization must have hierarchy and diversity. The universality of this organization throughout the animate and the inanimate realms is key to understanding this phenomenon.

Government is a complex of rules that act as channels, which guide and facilitate the movement of humanity (people and goods) on the

world map. Without these channels we would be stuck, like the water in a swamp, and stuck means poor, hungry, cold, unhappy and short-lived.

Better ideas have the same physical effect as better laws and better government. The urge to improve, to organize, to join, to convince others and to effect change is a trait that we all share. This is why the human & machine species evolves toward greater, easier, more efficient, farther and longer-lasting movement. This is evolution, loudly. Evolution is inevitable. We read and hear about it every day. The evolutionary design tendency toward liberty and better government is part of nature, and this is why it is unstoppable.

The Physics of Life clarifies the meaning of evolution in its broadest scientific sense, as physics. Evolution means the changes that occur in flow organization over time, and how these changes occur in a particular direction, as if with objective, intention or purpose. This is as true for technology, athletes and animals as it is for geophysics. Any evolution or design change that is useful is measured the same way in economics, technology and animate and inanimate systems. It is useful if it facilitates global flow. It is more useful if it liberates more flow. This is particularly evident in economics and the evolution of technology. Evolution never ends.

"Believe those who are seeking the truth. Doubt those who find it."

André Gide

Knowledge is the ability and action of the human & machine species to effect design change. Knowledge is the know-how that spreads incessantly. Information is not knowledge. Data are not knowledge either. The data do not spread by themselves but by the carriers of knowledge: the individuals. Engineers are among the carriers. They are scientists, not tinkerers. Their insights stem from thinking of images in motion and the origin of the power that drives every motion.

Inventors are carriers of knowledge about design change. They constantly question what they carry, discarding what does not work and carrying the better design change forward.

"Evolution" is almost always associated with "life," and as a consequence the scientific debate on evolution is about examples from the biosphere. All the flow systems of geophysics were evolving long before there was a biosphere: turbulence, river basins, lightning, atmospheric and oceanic currents, tectonic movement, beach migration, sand dunes and many more.

Evolution in all the kingdoms of nature, inanimate and animate, is like a movie of the development of a river basin. Tiny gates for tiny streams open and the river grows and floods the plain. So exquisite is this design that the city downstream of the flood is powerless to stop it. Water pushes little grains, small debris and large tree logs out of the way, and it breaks through riverbanks left from the previous season. Geophysicists call this phenomenon "erosion," but this word does not do justice to the shaping and constructing that really goes on. Erosion has the same Latin origin as rodent, the verb *roděre,* which means to gnaw, to wear down with the teeth, to destroy. The river waters do not cut indiscriminately; they cut in special places, and build in other places, at particular times. The result is flow organization, order—the unstoppable flood during the rainy season. The flood has the same flow design as the branching architecture of the tree. The flood is the tree architecture of the flow of water on the landscape. If the flood were not organized to invade the plain efficiently with tree-shaped hierarchical channels, nobody would have to run from its path. The plain would be nothing but wet mud.

A movie about the evolution of a river basin would also show the visible part of the evolutionary design of the relief of the entire globe. Start from the physics principle, which accounts for the natural tendency of rainfall to generate an architecture of channels and

wet banks that offer progressively easier access to the sea. Assume, for the sake of the argument, that the falling rain is uniform and steady, which would mean that the flow rate of the water mass carried from the wet plain to the river mouth is constant over time. The urge of the river basin architecture to evolve relentlessly toward easier access means that the relief of the landscape should evolve toward hills and mountains that become less tall over time. Easier flowing means less gravitational potential energy needed to drive the flow. This is what happens in nature, and why the phenomenon of erosion, as physics, is the same phenomenon as river basin evolution toward better-flowing tree-shaped designs.

If this is so, then why hasn't the earth's crust become perfectly flat? Sure, the plains are flat, but why are the mountains as permanent-looking as the plains? The reason is that the mountains keep rising while the river basins of the world keep shaving them down. A balance between the two effects rules the phenomenon that we see as relief. The mountains rise because of volcanic action and the collision of tectonic plates. The solids brought upward from the bottom are then brought back to the bottom by the rivers, through erosion and later sedimentation. This cyclical motion of the solid crust is what the mixing of the earth's crust is all about. This loop of circulating solids is akin to the eddy of turbulence. It is as big as the globe, and its life is as old as big history.

How do we know this about the cyclical mixing of the earth's crust in big history? When I was growing up, I spent many summers climbing the Carpathians. I remember being puzzled by the sharp canyons that several rivers had carved straight across the mountain chain. The explanation I was given, that the river erodes the rock and carries the debris downstream was correct, but far from satisfactory. To cut through the mountain, the river would have had to flow uphill, which is nonsense. The natural direction of the river would be along the mountain range, and eventually around it.

Unless the river is older than the mountain. It is only in this movie that the canyon could have been born. The plain with the river channel rose very slowly on the way to becoming the mountain range of today. The river kept on flowing, and kept on sawing through the rising crust.

* * *

You see, to have science, one must question. To have all the good things that sustain life, from science to technology and wealth, one must have the freedom to question. It is no coincidence that the societies that lead the world in movement, science, ideas and wealth (figure 1.2) are those that encourage the young to question reality and authority.

The hardest things to question are the most common occurrences. Why do they take such a long time to be recognized as natural tendencies (phenomena), and even longer to be recorded in physics with a short statement, a first principle? Because the evolution of the human mind is an integral part of the evolution of the human & machine species; it is natural to adapt and change in order to survive when struck by unexpected dangers—environmental, animal, and human. This is why the first thing we question is the unusual, the "surprise" (which, not surprisingly, means being grabbed from above, as if in the claws of a predator). The things that we tend to question the least are the familiar, the nonthreatening. This is why *new* questions in science are rare.

It is my hope that this book will empower readers with a new view of the globe as a spreading vasculature of analogous flows of populations, autos, air traffic, governments and many more. That it will show them how the urge to have better ideas has the same *physical* effect as the urge to have better laws and better government. I use the

term "urge" in the most general sense, to cover other terms in circulation, for example, natural tendency, impulse, intentionality, drive and instinct.

The urge to improve, to organize, to join, to convince others and to effect change is a trait that we all share. This is why the human & machine species evolves toward greater, easier, more efficient, farther and longer-lasting movement. This is evolution, naked on the table, and it is also, ultimately, the basis in physics of sustainability and how sustainability is achieved.

I grew up under communism in Romania, in Galati, a city near the Danube Delta. There were no passports, and we could not leave the country. But I could see oceangoing ships, their names and colors, and the foreign sailors in port. How this nourished my imagination!

I was deeply into the novels of Jules Verne and other writers popular with my parents' generation. Under communism, these old novels were the only stuff worth reading. The kids in my neighborhood passed them from hand to hand.

Forget about my imagination! The books by Jules Verne had the original illustrations of Captain Nemo and the *Nautilus* and all those faraway places in *Five Weeks in a Balloon* and *Around the World in 80 Days*.

From these books I learned that the movement of the world was flowing and changing to flow better. I could see it around me. When I was growing up, there were side-wheeler steamboats traveling the Danube. As I grew older, these were replaced by diesels. Right before I left Romania, hydrofoils appeared. I saw for myself the evolution that was visible in the imagination of Jules Verne and the drawings of Da Vinci.

I never had an urge to see my books' inventions in reality, perhaps because the urge was satisfied by the progress I saw as I was growing up. I saw side-wheelers become hydrofoils and the horse-drawn wagons on my street replaced by cars. Even though my parents did not

have a car, I could ride in one and feel the wind blow in my face. The train was a thrill. I was in awe of airplanes. You could say that I was rooted in the 1800s.

Now, human beings are part of a living system as big as the globe. The human & machine species is evolving every second, and I know it will get even better. It's all flowing, changing and really, really astonishing.

This page intentionally left blank.

2

What All the World Desires

There is a great fascination with wildlife, as shown by the audience for everything from glossy nature magazines to animal documentaries on TV. The more technology advances, the more the camera zooms in, and the louder the scientists exclaim that they have discovered something.

The images of nature at work are indeed fascinating. A popular documentary is about the wisdom of the ants, those enormously numerous and simple beings that live and work as an organized society. The commentator of the documentary tells us that the ants demonstrate wisdom because "the whole" benefits from their organization, not the individual. So effective is this wisdom of the ants in aiding their survival that the commentator wonders about the wisdom of humans, who seem to be fixated on optimizing every little thing for the maximum economic advantage of the individual.

We are way off the mark if we put the wisdom of the ants ahead of the wisdom of humans. The question that should be addressed is why