Adrian Bejan

FREEDOM *and* EVOLUTION

Hierarchy in Nature, Society and Science

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Preface

Evolution is the defining phenomenon of nature. Everywhere we look what we see is evolving becaue it is free to move and morph. Without freedom to change, there is nothing, no design, no evolution, and therefore no future.

Freedom is everywhere because evolution (design change) is everywhere in the inanimate, animate and human realms. Yet, unlike evolution, freedom is not a scientific subject. This struck me as strange. It is as if scientists are afraid to speak the word "freedom" even though every day they rely on the reality (the physics) behind that word. For example, every single book of thermodynamics is filled with analyses and designs of "processes". The definition of process is the change in the description (the "state") of the system. Clearly, if the system is to change, then it must have in its description the property called freedom.

It's not surprising that freedom has been overlooked in physics. The more common a physical presence, the more likely it is that it is overlooked. It happened this way with gravity, sound, turbulence, and fish swimming. It took time for questioners to be born, and for physics to expand over the newly identified territory.

The purpose of this book is to present the predictive theory of evolution. It is to establish firmly the concepts of freedom and evolution in physics. The approach I have chosen is that freedom is physics, not opinion. This book is not about the politicians' narrative. All the ideas and examples in this book were published based on peer review in physics, biology, and engineering science journals. These sources are indicated for further consultation at the end of each chapter.

Like everything else that is physical (i.e., part of nature), freedom is measurable. Freedom is the measurement of how many physical features are free to be changed in the configuration of the system. Measurable is also the physical effect that the ability to change has on other measures of system performance such as efficiency, power, robustness, resilience, and life span. In human-made designs, freedom is also measured as the number of "degrees of freedom" that is present in the model (the facsimile) of a natural flow system. Degrees of freedom are those palpable features that can be changed freely and *independently* of other palpable features.

Along with freedom and evolution as physics, other concepts acquire a solid scientific footing: complexity, images, drawings, diversity, hierarchy, social organization, ideas, discipline, and the evolution of science itself. All these concepts belong in scientific discourse, in physics. Why physics, because physics is the science that covers everything. Its concepts have unambiguous meanings. They are useful, and they owe their existence to freedom as a physical feature of everything that moves, flows, and morphs.

Science evolves because of freedom, and freedom thrives because of science. It is easy to create in freedom—just think of the history of art and science. Look at where artists and scientists were and where they lived and created. Their names speak of geography, history, culture, wealth, and the physical movement of free people with ideas and freedom to question and change the status quo. Free migration was key to their salvation.

This book will empower the reader with a science that covers territories that so far were not associated with physics: economies of scale, diminishing returns, hierarchy, wealth, social organization, the spreading of ideas, and scientific thought. Empowerment happens in two ways: readers will understand better the world around them and they will apply that understanding to effect change faster and more effectively. Physics tells us why things must be the way they are, and also that they are the givens that you must know in order to improve life and society. Things that appear disconnected and random are fooling us: they are intimately connected, hierarchical, flowing together and along with us, and thriving because of freedom, organization, and evolution.

Society is an earth-size living organism. The larger city is a bigger and more efficient mover than the smaller. This is why when the city is thriving the smaller settlements and companies are joining the bigger, why people migrate from the countryside to the city, and why in the industrial age the global society is evolving from peasant to urban. When the city ceases to thrive, the migration is the other way, toward the countryside.

This story of science addresses head-on and nullifies contradictions that spring up in our minds, for example, freedom versus inequality, freedom versus rules and discipline, rigid hierarchy versus evolution, rules versus random diversity, and evolution versus seemingly stable design.

Key is the image of evolutionary design. Reading this book you will find yourself imagining "movies" of rivers flowing, animals running, pedestrians walking, and people riding on buses, trains, and airplanes. The fact is that nothing moves unless it is driven. Pushing comes from power, and power comes from fuel for machines and food for animals. Once a natural system moves, it continually evolves its configuration toward flowing more easily, a set of goalposts that progress keeps moving farther down the field. As systems evolve, grow, and become more efficient, they also become more complex. Why? Because joining and moving (flowing) *together* requires less power than moving individually. This is the physics basis of "economies of scale" and its most obvious manifestation: social organization.

The same physics principle accounts for the fact that river systems evolve into embroideries of small tributaries flowing into a major river, and why a peloton moves more quickly than an individual cyclist. The bigger stream, animal, and vehicle are more efficient movers than the smaller. The hierarchical system with many small and few large movers is more efficient than the "one size fits all", though also more complex.

It follows that in the life movement of a population, what we commonly refer to as the economy, the amount of fuel consumed by the population is directly proportional to its annual wealth, the gross domestic product (GDP). So, physical movement (the flow) and economics are two sides of the same coin. The same hierarchical flow architecture accounts for both.

I formulated several other "big questions", and I treated them the same way, based on physics. The complexity, diversity, and apparent unpredictability of nature are distilled in Chap. 1 to three main ideas:

First, designs are everywhere, around us and inside of us: tree-shaped flows, round cross sections, and rhythms such as inhaling and exhaling. Evolution of design is a universal, unifying phenomenon of nature, and it is predictable based on its own law of physics, the constructal law (p. 5).

Second, nature is a rich weave of "engines" connected to power-dissipating systems that act as "brakes". The engines and brakes move hand in glove, and evolve with freedom.

Third, humans and their contrivances (machines, artifacts, add-ons) are like everything else that moves and evolves on earth. None of the evolving nature would be possible without freedom.

It is easier and more efficient to move a unit of something together with other units (in bulk) than to move it alone. The big size helps in many ways, yet, not all moving things (rivers, runners, fliers) become one big mover. The reason is that on earth all the movement happens between a point and an area (or a volume), not along a line between just two points. On an area, movers have freedom to access in all imaginable directions. They "scan" the area with a hierarchy of movers, on patches that form a hierarchical mosaic. Economies of scale collide with the reality of space (areas, volumes), and give birth to hierarchy.

The diversity of hierarchical flow architectures covers the broadest spectrum accessible to human observation: all size scales, animate, inanimate, human made and not human made, and steady and time-dependent (Fig. 1). Examples detailed in this book are river basins, human settlements (city rankings), sizes versus numbers of trees in the forest, university rankings, and rankings of the highly cited authors.

The nonuniform distribution of wealth is predictable because it is due to the evolutionary architecture of all the streams of a live society. The physical movement on the surface of the earth evolves naturally as arborescent, hierarchical flows. The GDP of countries all over the globe is proportional to human movement because it is proportional to the annual consumption of fuel, which drives all human movement. More economic activity means more fuel consumption. Wealth inequality becomes more accentuated as the complexity of the movement becomes more accentuated. When added to the natural design, artificial design features

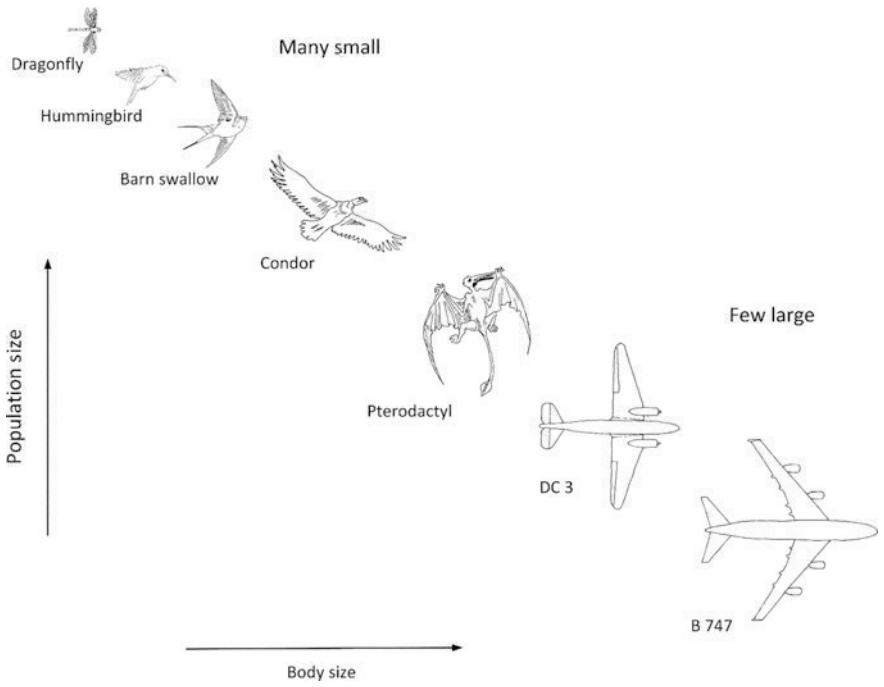

Fig. 1 Hierarchy in how animals and humans fly on the globe: qualitative distribution of population sizes versus body sizes (Drawing by Adrian Bejan)

decrease in wealth inequality. Trade routes are refracted paths for human movement on earth, which facilitate the movement.

Why does social organization happens by itself? Why does the organization becomes more hierarchical and unequal when the flows of society increase? In this book, such questions are answered from physics with two models, one without human society (river basins) and the other with human society (the distribution of hot water over an inhabited territory). The results from the two models are similar, except that in the model with human society the distribution of flow is less unequal. The reason is that the overarching presence of purpose (objective) at the scale of society controls inequality. Inequality persists even when the natural hierarchy of channels is replaced by artificial one-size channels everywhere. The spreading of individual innovation events over the populated territory benefits the whole society, in addition to benefiting the innovator.

There is no contradiction between freedom and reliance on discipline. In fact, the contrary is true: the scientist who possesses the disciplines is the most free to venture into new domains of knowledge. Disciplines are essential, empowering, and liberating for the scientist.

Complexity, organization, and evolution in nature are most powerful and useful when pursued as a discipline. A discipline has precise terms, rules, principles, and usefulness. A drawing has size, meaning (a message), and svelteness (the thinness of its lines). Drawings are useful when they are simple, easy to make, and not too large or too small. Icons and golden-ratio rectangles emerge from the human tendency to communicate more easily and faster. This is why features that are being perceived as attractive and beautiful are worth keeping.

Why is there so much diversity? Why don't we all look the same? Why are our occupations and contrivances diverse and becoming even more diverse? The answer lies in the freedom that all flow architectures have in how they spread, migrate, interbreed, and combine with flow designs that they encounter in their paths. This happened to the human flow on the globe. The human body architecture diversified as the first humans migrated out of Africa, to the north and the east. Along the way, humans have diversified as specimens of one "human and machine species".

The diversification of the machine part is evident in modern and contemporary times as the evolution of science and technology. The diversification of mechanics into thermodynamics and its many subfields accounts today for engineering sciences of many kinds: mechanical, civil, electrical, chemical, petroleum, nuclear, aeronautical, and more. The diversity of the human and machine species is of the same nature as the evolution of "niche construction" in animal evolution.

With freedom comes evolution with all its visible features: complexity, diversity, hierarchy, size, and free choices. Evolution—its future and its past—can be predicted. Detailed in this book are three predictions: one animate (animal locomotion), another inanimate (river basins), and the third about the human and machine species (aircraft). Many more predictions are available, for example, the cross sections of jets and plumes, the growth of snowflakes, the life span and life travel of animals and vehicles, the lung architecture, and the main measures of animal locomotion design (speed, frequency, force). Fundamental, for physics, is that a large architecture is not a magnified facsimile of a small architecture.

Finally, if evolution is so ongoing and everywhere, why do so many things look as if they are stuck in time? The reason is the phenomenon of diminishing returns, which is observed in freely evolving flow architectures that have become "mature". New changes have only marginal or imperceptible effect on the broad outlook and performance of the mature architecture. Examples that exhibit diminishing returns are the flows through tubes with freely morphing cross sections, vasculatures that connect the perimeter of a circle with its center, cantilever beams loaded with weight, and modern steam turbine power plants.

The evolution of science is a manifestation of the physics of freedom, access, and social organization. The physical movement of the individual generators of science is organized nonuniformly, hierarchically on the earth's surface. As society develops, it moves more, produces more, and generates more changes when it is endowed with freedom, free questioning, and self-correcting.

Freedom to change is the track on which the evolution train runs to join the other trains of science (e.g., Fig. 1.3). It is useful to know why the track is so "smart" that it led the designs of geophysics and biology to levels of perfection that continue to amaze us. It is useful to know how to use the evolution track so that our own artifacts evolve faster and more economically to even higher levels of efficiency, so that our own life as the human and machine species continues to become more free.

Give nature freedom, and nature comes back to life.

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Contents

About the Author

Adrian Bejan received the Benjamin Franklin Medal (2018) and the Humboldt Research Award (2019) for thermodynamics and the consructal law of natural design and its evolution in science and social systems.

His degrees are from the Massachusetts Institute of Technology: B.S. (1971, Honors Course), M.S. (1972, Honors Course), and Ph.D. (1975). He was a Fellow in the Miller Institute for Basic Research in Science, at the University of California, Berkeley (1976–1978). At Duke University, he is the J. A. Jones Distinguished Professor since 1989. He has authored over 30 books and 650 peer-refereed journal articles, and has been awarded 18 honorary doctorates from universities in 11 countries, from France to Azerbaijan, and from Brazil to South Africa.

Professor Adrian Bejan's impact on thermal sciences is highlighted by original methods of theory, modeling, analysis and design that today are associated with his name: life and evolution as physics, constructal law, entropy generation minimization, scale analysis, heatlines, temperature-heat (T-Q) drawings, and many more. He has received the highest international awards for thermal sciences, and is a member of the Academy of Europe.

Other Books by Adrian Bejan

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Chapter 1
Nature and Power

People like to say that nature is complicated and becoming even more complicated. A lot has been said about diversity, complexity, unpredictability in nature, and more recently about the law of physics that accounts for all such observations. In this chapter, I distill this body of knowledge to just three ideas:

The first is that designs (images with meaning) are everywhere, around us and inside of us. Most obvious and best known are the tree-shaped designs, the arborescent flow structures of the river basins, human lungs, lightning, vascular tissue, urban traffic, snowflakes, river deltas, global air traffic, and vegetation (Fig. 1.1).

Many other images go unnoticed, as if taken for granted. One class is the round cross sections of ducts, and they cover the board from blood vessels, pulmonary airways, and earth worm galleries to the "pipes" carved by rainwater in wet soil and the hill slopes of the smallest rivulets of the river basin. Technologies of many kinds employ round ducts, and for a good reason: they offer greater access to what flows, greater than in the absence of round cross sections.

Less known are the rhythms of nature, the designs that represent organization in time, not in space. In most places, the flows that sweep areas and volumes flow in two distinct ways. In the river basin, the water first flows as seepage in the hill slopes (by diffusion, called Darcy flow), and later as streams in river channels. This combination is the physics of what others call "anomalous diffusion". The first way is slow and short distance, while the second is fast and long distance. Mysteriously, it seems, the water spends roughly the same time by flowing slowly (as seepage) and by flowing fast (as channel flow). The equality of times is the rhythm, and it is predictable from physics.

Oxygen reaches the lung volume thanks to the same design of two flow mechanisms. The short and slow is the diffusion across the vascular tissue of the alveoli. The long and fast is the flow through the pulmonary tubes. Diffusion and tube flow take the same time, which is the time of inhalation. Carbon dioxide is evacuated in the opposite direction, from a volume (the thorax) to a point (the nose). The same two-way combination facilitates the flow of carbon dioxide, first by diffusion across

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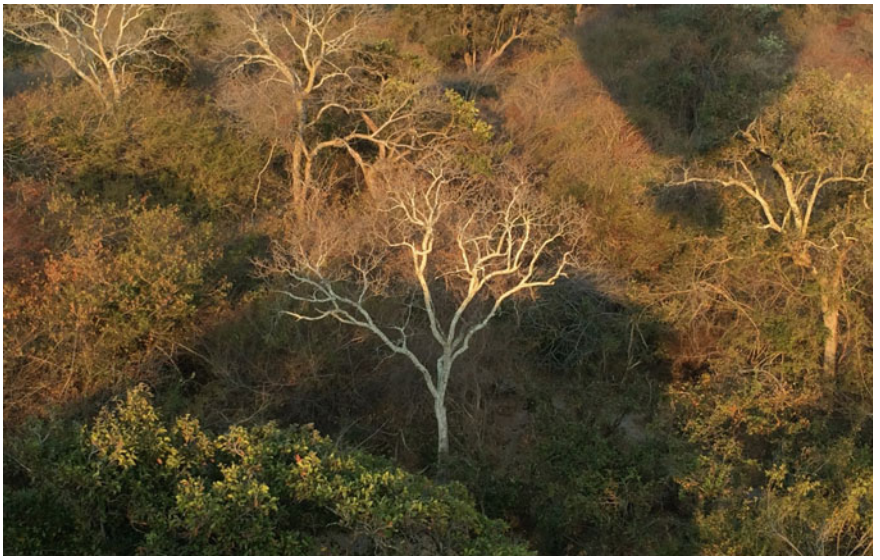

Fig. 1.1 Live and dead trees on Kapinga Island of the Busanga Plains, Zambia (Hot air balloon photo at sunrise: Adrian Bejan). Under this forest, the soil is a vast and tightly connected hierarchical vasculature of fungi that transports to the live trees the nutrients from the fallen trees, leaves, and fruit. The hierarchy of the tree society is visible above ground: few large thrive together with many small. Like a country, the tree society is held together by the ground, which is a live flow system vascularized with a hierarchy of diverse flows of water, nutrients, and animal life, constantly morphing in freedom

alveoli walls, and later by tube flow at larger dimensions. Diffusion time is the same as tube flow time. Even more intriguing is the fact that the point-volume flow (inhaling) takes the same time as the volume-point flow (exhaling). The flow direction (in and out, inhaling vs. exhaling) is not the idea, the rhythm is.

The same temporal design governs the flow of nutrients via blood circulation. Diffusion across the walls of the smallest blood vessels (the capillaries) is the short and slow way to flow. Stream flow along vessels larger than the capillaries is the long and fast way. The diffusion time is the same as the duct flow time. This is true for both directions of flow, in the arterial system (from lungs to whole body) and in the venous system (from body to lungs). In both directions, the flow is a design consisting of two tree flows, a volume-point tree connected to a point-volume tree where the point is unique (the heart), and the volume alternates between body and lungs. The time scale (the heartbeat) is the same for both directions of blood flow.

Rhythm and tree design govern the flow of water on land. The area-point flow of the river basin is followed by the point-area flow of the delta. The point in this image is one: the entrance to the delta. I grew up at such a point, on the Danube. Vegetation design is the coupling of two trees, and the base of the trunk is the connection. The root system is the tree that carries water from the wet ground (a volume) to the base of

Fig. 1.2 How the ski slope "exhales" its population: hierarchical basin of skiers flowing down the side of a mountain covered with fresh snow powder (Photo: Rick Frothingham 2011; with permission)

the trunk (a point). The tree above ground carries the same stream of water upward, from the base of the trunk to the volume that contains the canopy and the dry air that blows through the canopy.

Diversity is part of the evolutionary design phenomenon. To appreciate its origin, think of how we all move through the seemingly rigid infrastructure of the city. We move with freedom. We make free choices all the time. Crowds flow as trees, from area to point and from point to area. In the early morning the crowd of commuters converges on the train station and the airport. It does so with hierarchy, with denser columns of people and automobiles on the larger and straighter streets that reach their point-size destinations. The canopy of this morning tree of human flow is the whole city area. In the evening, the same crowd flows in the opposite direction, from the point to the area (the city). In the morning, the city exhales people, and in the evening it inhales.

There are many other points (schools, offices, theaters, churches, and stadiums) that act as "valves" that open the sources and sinks for moving crowds. That is the design of human movement everywhere on earth, and it is like air respiration, inhaling (point to area) alternating with exhaling (area to point). It is a rhythm. Skiers on a snow-covered mountain illustrate how this flow architecture evolves (Fig. 1.2).

There are many more cases that indicate the time direction of design change, which we call *evolution*, and they seem even more dissimilar and unrelated in comparison with the examples mentioned above: