Chapter 2
Toward a Quantitative Unifying Theory of Natural Design of Flow Systems: Emergence and Evolution

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2.1 Quality Design Prevalence in Natural Systems

The idea of beauty and quality of design of the natural systems found a broad consensus in the natural philosophers [1]. This is because living systems are wonderfully adaptable and can survive in a complex natural environment. Attempts to imitate living systems have been made since ancient times. The identification of animals as streamlined bodies with applications to manufactured devices for drag comes from Renaissance period [2, 3]. Leonardo da Vinci recognized the importance of the relationship between design and function. He noticed that a fish could move through water with little resistance because its streamlined shape allowed the water to flow smoothly over the afterbody without prematurely separating [4]. Da Vinci's flying machines powered by man were drawn in the 1490s based on the observation of birds [2] (Fig. 2.1).

In the seventeenth century, Borelli, together with Robert Boyle, René Descartes, Niels Stensen, and others, was the founder of an important intellectual movement known as iatromechanism [5]. According to Thomas Hall [5] "For Borelli, living bodies are machines. The life of the machine is the totality of movements exhibited by the moving parts and by the machine as a whole. The whole machine is an assemblage of smaller component machines." Borelli [6] also attempted to copy animal characteristics in a submarine design. Buoyancy control was based on the swim bladders of fish and propulsion control was obtained by oars acting similarly to paddling feet of geese or frogs.

The adherence to biological principles and designs for an enhanced performance influenced different areas of knowledge and last until today [7, 8]. The slogan "form follows function" became the tune of modern architecture [9]. This idea influenced

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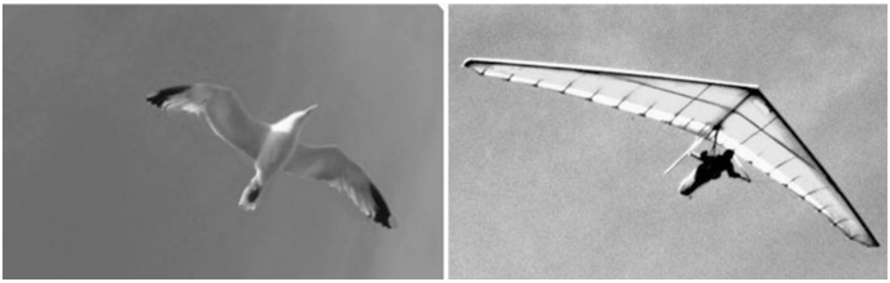

Fig. 2.1 A bird and a flying machine

the organic architecture of Frank Lloyd Wright and follows. In modern engineering, the idea is also to use biological inspiration to engineer machines that emulate the performance of animals. This biomimetic approach[1] [10] attempts to seek solutions for increased efficiency and specialization because consider that living systems have already performed the cost–benefit analysis (i.e., optimizing specific design for particular functions) due to process of "natural selection." Not long ago, scientists designed an electronic camera that mimics the shape of the human eye for improved imaging [12]. This design prevents the distortion that normally occurs at the edges of flat lenses.

The designs exhibited by natural systems may be target for technology transfer and to reduce the time of development of innovative solutions. Although, strict adherence to these designs is not always synonymous of good practical results [13, 14]. To prevent failures, a clear understanding of why a particular design is successful and the circumstances that make it successful is needed.

2.2 Design and Physics Principles

Since Anaximenes of Miletus (585–528 B.C.) laws are considered operative throughout the Nature [15]. This constitutes a magnificent triumph of reason and observation: laws tell us how things operate and can guide us in the quest for news knowledge. The invariance provides a structure and coherence to the laws just as the laws provide a structure and coherence to the set of natural events. In fact, the invariance of the laws of Nature under space–time translations allows applying them at different times and places. So, laws form the bedrock of Physics.

During the last century, quantum theory and relativity have profoundly modified the laws of mechanics. The whole body of thermodynamics, instead, has remained

[1] The term "biomimetics" was conceived by Otto H. Schmitt in 1969 from "bios" meaning life and "mimesis" meaning to imitate [11]. Other term that is often used is "biomimicry," which has been put forward as a method of working that seeks sustainable solutions by emulating nature's patterns and strategies (e.g., a photovoltaic cell inspired by the structure of a leaf).

untouchable.[2] The zeroth law defines a useful property "temperature" (and states that the equality of temperature as necessary and sufficient condition for thermal equilibrium), the first law defines a useful property "energy" (and asserts that energy is conserved), the second law asserts the existence of an extensive property "entropy" (and states that the entropy of an adiabatically isolated system never decreases in time), and the third law define a state known as "absolute zero" (and relates the entropy of a systems to its absolute temperature).

The generation of configuration (design) is a universal phenomenon that occurs in every flow system. In the struggle to understand this phenomenon, Adrian Bejan comes to a new and comprehensive law of design generation—the constructal law. The ubiquitous generation of configuration is, like other phenomena, covered by a physics law that states that "For a finite-size flow system to persist in time (to live) it must evolve such that it provides greater and greater access to the currents that flow through it" [17, 18].

The generation of flow design (configuration, shape, and structure) belongs in thermodynamics [19–22], and completes the four solid metacarpal bones (i.e., previous four laws) that form the structural frame of the hand that holds the modern science. This new law asserts that for any flow system there is a property "configuration" (and relates the generation of configuration to its greater access to flow[3]). Flows occur against resistances (imperfections) that constantly try to slow down. Design is the constructal path to persist in time (to survival). Each system acquires configuration (design), in time, by replacing an existing configuration by a design that best allocate imperfection (resistances), providing an easier flow access. Therefore, the mastery of this law is essential in the analysis of systems far from equilibrium.

2.3 Thermodynamics Laws, Time, and (A)Symmetry

Regarding the influence of the time, laws may be separated into two components: the description of the set of states that the system can be in at any given time and how states change with time. In mechanics these two components are called "kinematics" and "dynamics," respectively. The question about preferred direction of action in time or time symmetry/asymmetry can be regarded within this framework.

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[2] "The law that entropy always increases, holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations—then so much the worse for Maxwell's equations. If it is found to be contradicted by observation—well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics, I can give you no hope; there is nothing for it but to collapse in deepest humiliation"—Eddington [16].

[3] "Maximum flow access" corresponds to minimum travel time or minimum transfer time [23]. Therefore, "for a finite-size flow system to persist in time it must evolve such that it provides a minimum travel time to currents that flow through it."

Although all processes must take place in accordance with the first law, the principle of conservation of energy is, by itself, insufficient for an unambiguous description of the behavior of a system. Specifically, there is no mention that every natural process has preferred directions of action in time. For example, in the formation of Benard cells (i.e., far from equilibrium phenomenon), the flow of heat occurs naturally from hotter to colder sites, and as the temperature of the bottom layer is increased, a stage is reached (critical temperature) where the liquid overcomes its internal resistance (viscosity) and begins to undergo bulk motion. The concept of energy (and energy conservation) is not sufficient to explain these things. Both, the reverse flow (cold to hot) and the immutability of configuration, are not in violation of the first law. In addition, so far as that law is concerned, the heat is transferred into the system and increases its internal energy, but if the heat source is disconnected, it undergoes a decrease in temperature and returns to the same internal energy state. Since it is possible to take the same amount of internal energy back, there is symmetry of state of the system.

The second law of thermodynamics points that the "forward" and "backward" for heat is not allowed in the sense that heat always flows from hotter to colder sites (i.e., energy always gets dissipated as heat—irreversibility). There is a "time asymmetry" or a "direction of time" or an "arrow of time." The second law states that $\frac{dS}{dt} \geq 0$, where S is the entropy and t is the time, and expresses a time asymmetry of the state of the system (i.e., "kinematics").

The constructal law points to another "arrow of time": an existing configuration morph toward easier flowing configurations to assure its survival (i.e., designs that provide less access to the currents are not allowed). This law tells how configuration changes with time in the quest for greater flow access (i.e., "dynamics"). Cells emerge when the temperature of the bottom reaches a critical temperature because cells facilitate heat to flow more efficiently into the colder sites. But they disappear as soon as the temperature drops below the critical temperature because cells are not the constructal paths that provide an easier flow access. The constructal law, as others "dynamical laws," admits time reversal symmetry.

It becomes apparent that the emergence of configuration, defined by the constructal law, requires that the entropy changes, rather than staying the same. Consider a Poiseuille-type resistive flow. The rate of entropy generated, S_g, is

$$\frac{dS_g}{dt} = \frac{VI}{T}. \tag{2.1}$$

Here V is the potential, I is the current I, and T is the absolute temperature. In terms of flow resistance R, (2.1) may be rewritten as

$$\frac{dS_g}{dt} = \frac{V^2}{RT} \quad \text{or} \quad R = \frac{V^2}{\left(dS_g/dt\right)T}, \tag{2.2}$$

$$\frac{dS_g}{dt} = \frac{RI^2}{T} \quad \text{or} \quad R = \frac{T\left(dS_g/dt\right)}{I^2}. \tag{2.3}$$

Maximum flow access means minimum resistance under constraints: constraint of constant I or constraint of constant V. According to the (2.2), minimizing the flow resistance for a specified potential, V, corresponds to maximization of the entropy generation rate. On the other hand, minimizing the flow resistance under a constant current, I, corresponds to minimizing the entropy generation rate (2.3). The meaning of (2.2) and (2.3) is double-fold: (1) the constructal law is connected with the maximization and minimization of entropy generation rate principles, and (2) as second law of thermodynamics is diverse of the principle of maximization/minimization of entropy generation rate, the constructal law is distinct of the second law of thermodynamics.

In summary, the constructal law may be connected with minimization/maximization of entropy generation rate and is essentially different from the second law of thermodynamics. Both laws share a preferred direction of action in time ("arrow of time") but with distinct time symmetry.

2.4 Natural (Constructal) Design of the Large and Small

Natural flow systems are complex and diverse. They cover several orders of magnitude in length and in mass.

Inanimate systems such as Nile and Amazon basins have lengths of 6,850 km and 6,700 km, respectively, and drain more than 3×10^6 km^2 [24, 25]. In the opposite length scales are the aerosols. Aerosols are solid or liquid particles suspended in air or other gaseous environment. Their particles sizes are in the micrometer and sub-micrometer range, and tend to combine with each other (agglomerate) to form larger particles. Living organisms cover more than 27 orders of magnitude in mass from molecules of the genetic code to whales and sequoias [26]. Even though, life uses the same reactions and chemical elements to generate a remarkable variety of forms and dynamical behaviors. Do these systems follow the same law of configuration (design)?

The constructal law is grounded on the idea that flow systems are not purposeless (the ultimate target is to persist) and are free to morph in time (evolve), under global constraints, to accomplish their purpose. Configuration is the constructal path to carry fluid, heat, mass, information, people, etc., in order to persist in the "arrow of time." Is this law of design real? Does it belongs to the world or merely reflect the way we speak about it? All scientific efforts are based on the existence of universality, which manifests itself in diverse ways and scales. In this section, we arbitrarily partitioned the scale spectrum into microscale, mesoscale, and macroscale [27] and reviewed some advances in the emergence of configuration, within these scales, in the light of constructal law. This is not an exhaustive list of examples, but it does reveal the depth that this law embodies.

2.4.1 Natural Design into Microscale Flow Systems

Nano- and micron-particle agglomerates often have dendritic shapes instead of spherical shapes. Why does it occur?

Consider that there are not electrically neutral surfaces in contact with the air [28], and the forces that make aerosol particles stick onto previously deposited particles are of the electrical type. Observation shows that there are two kinds of configurations: spherical and conically. The volume growth in time of a spherical agglomerate shape, V_{sph}, is given by [29]

$$V_{\mathrm{sph}} \sim K^2 t^2, \tag{2.4}$$

while the volume growth in time of an agglomerate of particles with the conical shape, V_{con}, is

$$V_{\mathrm{con}} \sim \left(\frac{q_{\mathrm{el}} K^{14/3}}{\mu_{\mathrm{el}}}\right)^{1/2} t^{7/3}, \tag{2.5}$$

where μ_{el} is the dipole moment, q_{el} is the charge and K is a quantity that depends of the particle size, dipole moment, electric charge, Cunningham correction factor, electric permittivity of the air, surface density of charge, and air viscosity.

According to the constructal law, the architecture of the aggregate of particles evolves in time in such a way that the global rate of accumulation of the particles is maximized (i.e., agglomerates the particles in the fastest way possible). The temporal evolution of the accumulation volume is presented in Fig. 2.2. This plot shows that at the critical time, t_{critical}, the volume of conical agglomerates overtakes the volume of spherical agglomerates. According to (2.4) and (2.5)

$$t_{\mathrm{critical}} \sim \left(\frac{\mu_{\mathrm{el}}}{q_{\mathrm{el}} K^{2/3}}\right)^{3/2}. \tag{2.6}$$

This means that the agglomerate must first grow as a sphere ($t < t_{\mathrm{critical}}$) and then change to a conical shape. The initial design (spherical) is replaced by a design (conical, tree-shaped) that agglomerates more easily. Experimental measurements reported in the literature confirm the main features of this constructal development [29].

Liquid droplet impact on a solid surface may present a disk configuration or develops needles that grow radially (Fig. 2.3). Bejan and Gobin [30] reveal that liquid droplet impact is a manifestation of the constructal law and also present a dimensionless number that governs the selection of geometry. This number is defined by the ratio of two lengths, the final radius of the disc that dies viscously, divided by the radius of the still inviscid ring that just wrinkles.

Transportation systems for the long-distance delivery and distribution of biofluids are essential for the multicellular organisms. The fluid with some

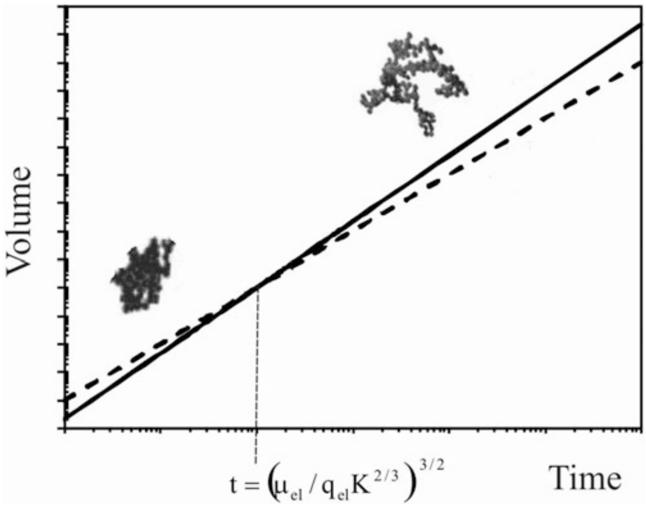

Fig. 2.2 Time evolution of the volume corresponding to conical (*line*) and spherical (*dashed line*) agglomerates

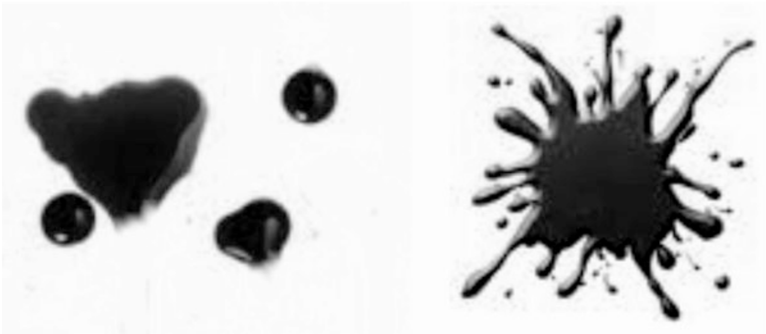

Fig. 2.3 Liquid droplet impact on a solid surface

dissolved components (oxygen, carbonic acid, mineral, and organic nutrients) must be delivered to a distributed set of consumers (cells, tissues, organs). Galen who lived in the second century A.D. and spent part of his lifetime in observation of the human body and its functioning, described the blood vessels as "trunks divided into many branches and twigs" that nourished the body [31]. Tree-shaped networks of tubes with decreased caliber are used to deliver these fluids (Fig. 2.4). It can be found in mammals, plants, invertebrates, and some others. In spite of their complicated topology and sizes (i.e., tubes may vary in diameter from micrometer to decimeter), they reveal a common design principle of construction in the nature. Vast measurements on different systems (i.e., arterial, venous, and respiratory systems; plant leaves; etc.) show that [18, 21, 31]

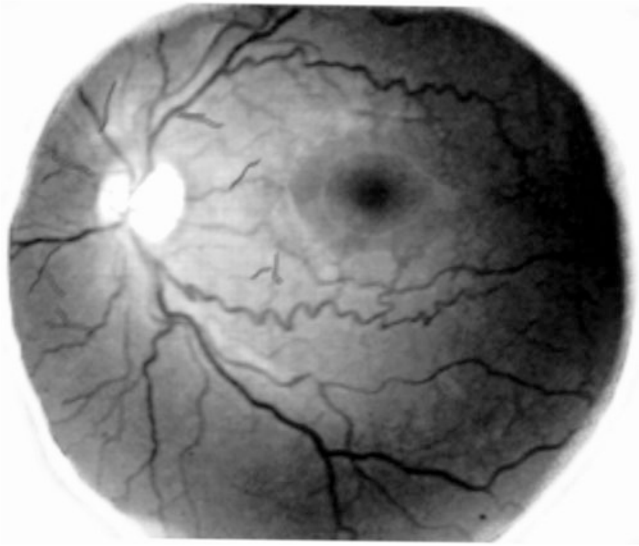

Fig. 2.4 Network of branching blood vessels in the eye (courtesy of UNL)

$$D_o^n = D_1^n + D_2^n, \tag{2.7}$$

where D_0, $D_{1,}$ and D_2 are the diameters of the parent and daughter's vessels at a bifurcation, respectively, and the power exponent n was found to be 3, except when the flow is not laminar ($n = 2.3$). Equation (2.7) is usually termed as Murray or Hess–Murray law.

Bejan et al. [32] focused on a stream that branch into tributaries streams in a constrained space. A steady incompressible flow through an assembly of ducts (T- and Y-shaped assembly depicted in Fig. 2.5) with negligible pressure losses[4] at bifurcation was considered. The objective was the maximization of the system performance by minimizing the global flow resistance of the fluid stream. They found that the exponent n of Equation (2.7) depends on the flow regime but it is independent of geometry of the configuration: for laminar flow n is 3 but for turbulent flow n is 7/3 (~2.3). Bejan et al. [32] also studied the relationship between the lengths of the parent and daughter's vessels (L_0, $L_{1,}$ and L_2). They found that the lengths are described by an equation similar to that of (2.7) (i.e., $L_0{}^n = L_1{}^n + L_2{}^n$): for laminar flow n is 3 and for turbulent flow n is 7. These are new results provided by the constructal theory [32].

[4] Wechsatol et al. [33] studied the effect of junction losses on the optimal geometry of bifurcation. For laminar flow, the junction losses have sizable effects on the optimal diameter ratio at each node of bifurcation only when the dimensionless parameter called svelteness, defined by the ratio between the external and internal length scales, is lower than the square root of 10.

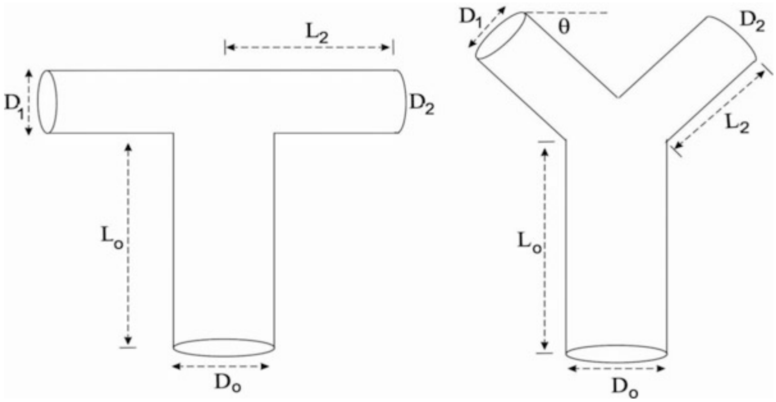

Fig. 2.5 T- and Y-shaped assembly of ducts (adapted from Bejan et al. [32])

Tree-shaped networks are also a manifestation of the constructal law. Bejan [34] and Bejan and Lorente [35] showed that the tree-shaped networks of tubes with decreased caliber, found in mammals, plants, invertebrates, and some others, occur if the purpose is to connect one point (source or sink) with an infinity of points (volume, area, and line), and what flows (i.e., fluid, heat, people, goods, or other) exhibit at least two regimes (e.g., slow and fast).

Snowflakes configuration is a manifestation of the constructal law and the explanation is also provided by Bejan [18, 36]. If the fluid temperature is slightly below the solidification temperature at an immobile fluid medium, latent heat is released at the solidification site and flows into the subcooled medium. The tree-shaped configuration of the snowflake is the one that makes it easier for the heat currents to flow from small areas to the entire volume. Turbulent eddy configuration has also a similar foundation: the trade-off between diffusion and convection (streams) mechanisms [18, 37].

2.4.2 Natural Design into Mesoscale Flow Systems

Lungs, kidneys, circulatory system, etc., and also colonies of living organisms (e.g., stony corals) are also examples of ordered solid configurations. Lungs, for example, are the organs specialized for oxygen and carbon dioxide exchange between air and blood [31]. Two flow mechanisms may accomplish this objective: diffusion and convection (streams). Therefore, the lung could be a ducts system or a simple single sac open to the external air from which the oxygen and carbon dioxide diffuses between the air and the blood. A duct system has a higher friction resistance than a sac (volume) open to external air [31]. Besides, the access time for a gas concentration to travel by diffusion and by "streams," through a characteristic length L, is ~ L^2/D and ~ L/u, respectively, where D is the diffusion coefficient and u the gas

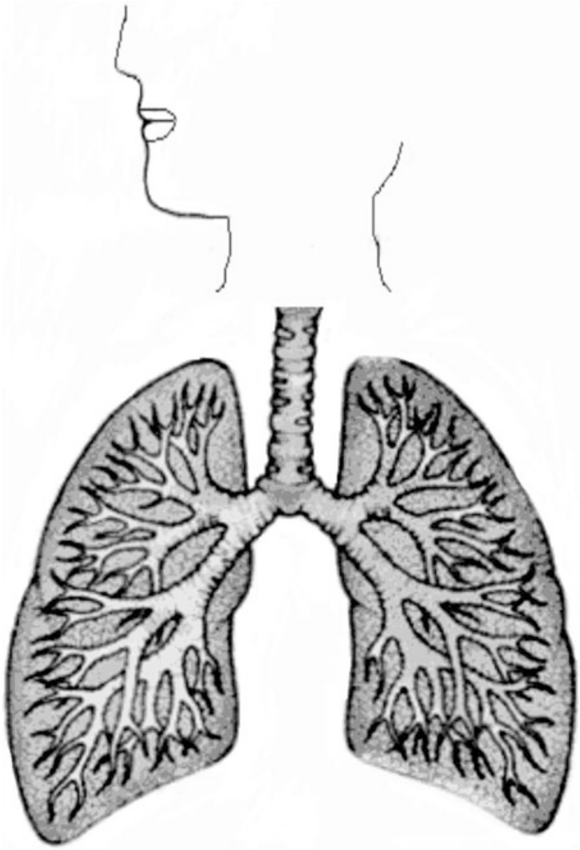

Fig. 2.6 Anatomy of the lungs

speed [31]. Consequently, the possibility of a simple single sac is clearly noncompetitive as compared to a ducts system: the former has an access time for streams flow of ~1 s (characteristics length ~0.5 m and gas speed ~0.5 m/s) whereas the latter has an access time of ~10^4 s (diffusion coefficient ~10^{-5} m^2/s). In summary, a duct system has a large friction resistance to airflow whereas the single sac has a large spreading resistance. Why are lungs tree-like structures?

The answer is provided by Bejan [18] based on the constructal law: as mentioned in the last section, if the aim is to connect one point with an infinity of points and there are different flow mechanisms to accomplish the purpose, the constructal path that emerges is a tree (Fig. 2.6). Tree-shaped networks act as basic supportive flow paths along which flows need to survive are propagated [18]. But what are the tree characteristics that provide the easiest way to supply oxygen to the blood and the drainage of carbon dioxide from it?

Dichotomy (pairing or bifurcation) is an optimized result in tree-flow structures provided by the constructal law (see for example, Bejan [18], Bejan and Lorente [21], Miguel [31]), as well as the relationship between successive duct sizes (see Sect. 2.4.1). The exact number of bifurcations was studied via the constructal law [31, 38, 39]. Assuming a Hagen–Poiseuille flow through the network, the global resistance to fluid flow after minimization yields the optimal number of bifurcations, N_{opt},

$$N_{\text{opt}} = 2.164 \ln\left[\frac{0.000235 D_0^4 R_{\text{air}} T_{\text{air}}}{v_{\text{air}} D_{\text{g}} L_0^2}\left(\frac{\phi_{\text{g},0}}{\phi_{\text{g}}} - 1\right)\right], \tag{2.8}$$

where v_{air} is the kinematic viscosity of the air, L_0 is the trachea length, D_0 is the trachea diameter, D_{g} is the diffusivity of the gas (e.g., oxygen or carbon dioxide) in the air, R_{air} is the air constant, T_{air} is the temperature, and ϕ_{g} and $\phi_{\text{g},0}$ are the relative concentration of gas in the alveoli and in the outside air, respectively. Based on data available in the literature for L_0, D_0 and ϕ_{g}, the optimal number of bifurcations is obtained by assuming a body temperature of 36 °C and taking all pertinent values at this temperature. Using these values in the previous formula, N_{opt} is 23.4 and 23.2 for O_2 and CO_2 transport, respectively. As the number of bifurcations must be an integer, the optimal number of bifurcations of the respiratory tree must be 23, which is a very well-known result in pulmonary physiology. In summary, the best configuration for lung is a tree with 23 levels of bifurcation (i.e., ducts system with a lower spreading resistance) that ends with alveolar sacs.

All the living beings are subjected to the same average environmental parameters. Therefore, the constructal law also predicts that it must exists a characteristic length D_0^2/L_0 (i.e., the ratio of the square of trachea diameter to its length) that is representative for humans [38, 39]

$$\frac{D_0^2}{L_0} = 8.63 \frac{LA}{V} \frac{v_{\text{air}} D_{\text{g}} \phi_{\text{g}}}{R_{\text{air}} T_{\text{air}} (\phi_{\text{g},0} - \phi_{\text{g}})}. \tag{2.9}$$

Here A is the alveolar area required for gas exchange, V is the volume allocated to the respiratory system and L is the length of the respiratory tree. Equations (2.8) and (2.9) clearly demonstrate that the number of bifurcations of the respiratory tree is determined by the characteristic length D_0^2/L_0, and this length is determined by the dimensionless number LA/V.

Stony corals and other colonies of living organisms (e.g., bacterial colonies) that cope with hostile environmental conditions (e.g., growing in sheltered sites or nutrient-poor water) develop branched configurations. Stony corals, for example, may present two flow "mechanisms" of growth: diffusion (compact and massive) and streams (tree-shaped). Besides, diffusion and convection (streams) mechanisms may also drive the water, with nutrients, that bath the colony. Configuration is the constructal path to survival by increasing flow access (performance). At sheltered sites, diffusion (high access time; high spreading resistance) is the dominant mechanism that drives the nutrients. Therefore, the action of the constructal law is evident: corals must grow as "bio-streams" (low spreading resistance) which provide the most direct path to the slow (diffusive) regions of nutrient transport [40]. On the other hand, at nutrient-rich water currents (i.e., streams with low spreading resistance) corals grow as compact structures (i.e., more effective to fill space) [40]. This subject will be further addressed at Sect. 2.5.

The majority, if not all, of complex systems have at least one common feature: they have a propensity to exhibit scaling properties [7, 26, 41]. The identifying signature of a scaling property is an allometric scaling law. These laws capture essential features such as configuration, organization, and dynamics of natural flow systems [7]. Therefore, they should be a manifestation of the constructal law.

Metabolic rate (or rate of energy use) is essential and limits almost all biological processes in microbes but also in mammals, birds, or plants. Since the important study of Kleiber in 1932 [7, 41], it has been known that the metabolic rate in most living organisms scales as approximately the 3/4 power of body mass. In 2001, this empirical allometric law was derived based on the constructal law [42]. Bejan and coauthors [21, 42] also showed that living organisms are built from the same "constructal paths" under the existence of the same powerful constraints at every level of biological organization (e.g., optimized space-filling, tree networks) because they have survived the process of natural selection.

Speed of flyers, land animals, and swimmers are in proportion to their masses raised to the power 1/6 and body movement frequencies (stride, flapping, and fishtailing) decrease with their mass raised to power (−1/6). These allometric laws are also covered by the constructal law [43, 44] and clearly demonstrate that the locomotion design in living creatures is ruled by the same law. The generation of constructal configuration in also visible on the allometric scaling laws for the breathing, the heart beating, hair coats of animals, etc. [18, 21], as well as, in several main features of vegetation, from root and canopy to forest, such as the scaling laws for the tree length, the tree flow conductance, and the ratio between leaf volume and total tree volume. [45].

2.4.3 Natural Design into Macroscale Flow Systems

The atmosphere is the blanket of air surrounding our Planet. Its circulation has configuration and is also a manifestation of the constructal law. The middle latitude atmosphere is filled of eddies, which manifest themselves as traveling weather system. As explained by Bejan [18, 46], eddies represent the best paths for the flow of momentum. Reis and Bejan [47] relied on the constructal law to predict the latitude of the boundary between the Hadley and the Ferrel cells, and between the Ferrel and the Polar cells (Fig. 2.7). These latitudes constitute the constructal partitioning of the Earth's surface with respect to the heat flow along the meridian. Other quantities such as the average temperature of the earth surface and the convective conductance in the horizontal direction are also determined based on constructal law. They also concluded that the poleward heat transfer is determinant on the flow structure.

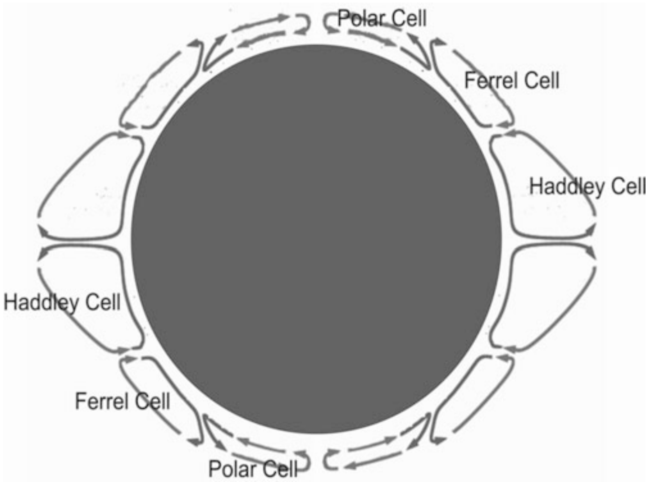

Fig. 2.7 The circulation of the atmosphere

Fig. 2.8 Tagus river basin through the Iberian Peninsula

The river basins are another class of tree-shaped configuration, like lungs, snowflakes, and corals (Fig. 2.8). The reason for this particular configuration is the same as for the lungs, snowflakes, and corals: the maximization of access for the flowing currents. The balance between dissimilar flow mechanisms (i.e., timescale of seepage down the hill ~ residence time in the entire basin) provides the maximization of flow access between one point and infinity of points, and vice versa [22].

River basins present geometrical features which can be measured, namely the area (measured on the vertical projection), the elongation ratio (the diameter of a circle with the same area as the drainage basin, divided by the basin maximum length), the relief (the difference of elevation between the highest and the lowest points of the drainage area) and the relief ratio (the basin relief divided by the maximum length of the basin). Scaling these geometrical features typically follows a simple power law (scaling law). These laws constitute the bond which united all of river basins. Well-known empirical allometric laws were derived from the constructal law as a result of minimization of the overall flow resistance [37, 48]: (1) the ratios of lengths of consecutive streams predicted by the constructal approach match Horton's law for the same ratio, (2) the number of consecutive streams match Horton's law of ratios of consecutive stream numbers, and (3) both Hack's and Melton's laws are predicted and the exponent evaluated accurately.

Cities are characterized by specific shape and dynamics. In time, they increase in size and number (evolve). Cities possess self-similar structures that repeat over a hierarchy of scales [49, 50]. Cities and countries are "giant" living organisms, which acquire and consume resources, produce and discard wastes, all the while employing energy for a variety of tasks: transportation, communication, maintenance, and reproduction of the complexity and organization.

In 1949, George Zipf devised his simple distribution law to explain the size cities in a country [28]. Giesen and Südekum [51] showed that Zipf's law not only satisfies the cities hierarchy but also German regions. Zipf distribution of city ranks versus city sizes can be derived from the constructal law in the same fashion as patterns of natural flow systems. Bejan [37] shows that this distribution can be obtained from the optimal allocation of flow paths to areas. This and others distributions have their origin on tree-shaped flow systems with patterns optimally allocated in space, in a similar way to scaling laws of river basins.

Another study shows that the carbon dioxide emissions to the atmosphere and the gross domestic product (GDP) from different countries scale with their "body" mass [41]. Countries have a body (structure in space), but also a rhythm (structure in time). Miguel [41] based on the idea of similarity between living organisms and countries presented several optimal features of intermittent flows (rhythmicities) for countries.

In summary, the emergence of scaling laws in river basins, cities, and countries (inanimate flow systems) is similar to the emergence of allometric laws in living beings. In both cases, they reveal similar basic supportive flow paths along which "order" need to survive is propagated. Therefore, scaling laws are a synonym of constructal systems.

2.5 Intraspecific Variability of Configurations (in Similar Systems) as a Manifestation of the Constructal Law

Micro, meso, and macroscales house diverse examples of intraspecific variability of configurations inside similar systems. Bacterial and stony corals colonies that cope with hostile environmental conditions develop branched configurations, while colonies that enjoy environments loaded with nutrients develop a compact shape instead [52–54]. Plants in soil have more open and more thinly branched roots than specimens of the same species which are growing under hydroponics regime [55]. Pedestrians typically prefer to move freely [56]. But in crowded spaces or when a stationary crowd stands in their way and needs to be overcome, pedestrians naturally organize themselves into streams (lanes).

Complexity is associated with an increased use of communication signals to organize a cooperative behavior [8, 57–59]. These signals do not elicit specific responses in themselves, but rather operate in a general manner to alter the probability that individuals will respond to other stimuli. For example, pheromone communication is an effective means of coordinating the activities of insect colonies such as ants, including food gathering, alarm, and defense, and even reproduction [59]. The growth of the coral or bacteria colonies also requires communication (i.e., sharing of information): between cells to create the individual polyp or bacterium, and between polyps or bacteria to create the colony. They must rely on chemical signals, electrical impulses, vibration signals, or other [8]. An organized collective behavior is also based on a coordinated and orchestrated interaction between people. They must share information—communicate. The communication can be verbal (i.e., communication that uses words) but also non-verbal (i.e., communication that includes eye contact, body posture and motions, positioning within groups, etc.) [8]. Therefore, pedestrians rely on communication to control specific pattern formation. Vision (and sometimes verbal communication) guarantees a precise control of the pedestrian position in space and time. In summary, communication signals are necessary for a specific pattern formation. The question to be answered is why they develop a particular configuration?

All these systems are not purposeless (i.e., they have objectives, functions to fulfill), and they are free to morph. So, according to the constructal law they should develop designs that represent the most competitive configuration for survival. A spherical massive volume (diffusive) is the more effective way to fill space and extract nutrients from the surrounding environment [40, 60]. But in a low-nutrient environment (or a hard agar surface or in a crowded open space) the formation of branches (i.e., bio-lanes, bio-streams, bio-rivers, or rivers of people) provide the constructal paths with low spreading resistance that enable coral and bacteria to thrive inside the nutrient rich region or pedestrians to penetrate the crowds [40, 60, 61].

Consider, for example, stony corals growing at a rate, u_c, of a few cm/year in a sheltered site, where water currents are practically absent and diffusion is the most important nutrient transport mechanism. The biological system starts to grow at its birth. Immediately after, nutrients close to the system are quickly depleted.

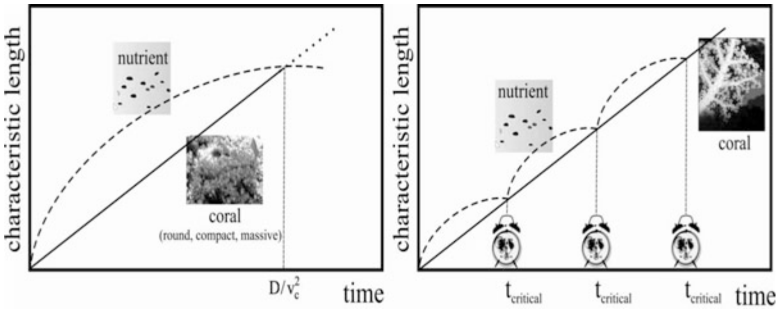

Fig. 2.9 Nutrient propagation and coral growth

This consumption of nutrients in the surroundings of the stony coral causes a decrease of nutrient concentration which triggers a diffusive wave of nutrients defined by a speed of propagation, v_d,

$$v_d \sim \left(\frac{D}{t}\right)^{1/2} \tag{2.10}$$

where D is the he nutrient diffusion coefficient and t is the time. The initial speed of propagation is greater than any growth speed of the living system, but decreases with the inverse of the square root of time. Consequently, the speed of nutrient propagation drops below the growth speed of the living system when $t_{critical} > D/u_c^2$. For $t_{critical} < D/u_c^2$, the round (massive) shape is the most effective arrangement for filling the flow space [40] but when $t_{critical} > D/u_c^2$, the coral begins to grow outside the nutrient diffusion region (Fig. 2.9). Then, branches (bio-streams, bio-lanes, or bio-rivers) develop because are low-resistance paths for nutrient access (i.e., the access time for stream paths is much lower than for diffusive paths; see also Sect. 2.4.2). As soon as the critical time is reached, the system comes out of the nutrient region. Then, each branch generates a new group of branches and the global feature of this scenario is the tree-shaped pattern (Fig. 2.9). In open sites where convection currents are important, the fluid velocity surrounding corals is much larger than the growth speed of the coral. Therefore, the critical time is never reached, and the system grows always inside a region where nutrients are ready available developing a round and compact design which is the most effective arrangement for filling the space [40].

Countries are also complex systems that are far from equilibrium because they are "alive" [41]. Prominent areas—the hubs of thinkers, makers, and traders—pump flows of energy, information and goods across the country. Night-time satellite images show that while these flows present a more massive configuration of brightly lit areas in developed countries/areas (i.e., resource-rich environments), they lead to a substantially more branched configuration of lights (light-lanes, light-streams) in underdeveloped ones [41, 62, 63]. Similarly to what happens in corals or bacteria or plant roots, the configurations of human activity appear to be optimally designed to fulfill their purpose, given the local constraints of economic development.

2.6 Survival in the World of Flow Configuration (Design)

> The task is, not so much to see what no one has yet seen, but to think what nobody has yet thought, about that which everybody sees.
> Arthur Schopenhauer (1788–1860) cited by L. von Bertalanffy's "Problems of Life" 1952.

Design—configuration, architecture, shape, structure, pattern, rhythm—is omnipresent in nature because all things have a design. The answer for the phenomenon of design generation lies directly in the constructal law of Adrian Bejan which constitutes an important contribution to the development of thermodynamics. Flow configuration emerges as a necessary consequence of being effective in a game plan catered to system strengths. Systems out of equilibrium, with internal freedom to morph, develop in time constructal paths which mean survival by increasing flow access (performance). The body of work reviewed here is not supposed to be exhaustive. For reviews that include the constructal view of manmade flow systems and social organization, see for example Bejan and Zane [64], Bejan and Lorente [21, 22, 62], Bejan and Merkx [65], Bejan et al. [7, 28], and Bejan [18, 37, 46, 66].

In summary, the evolution of systems is strictly connected with the possibility of their morphing configuration, permitting that the new configurations replace existing configurations, to perform better (constructal law). This self-standing law of design has both local and global significance. It shows a fascinating connection between the Nature as a whole and what this law holds in our world. The paths of all natural flow systems (i.e., animate and inanimate systems) are drawn together and can be described and understood under a unified view.

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