Constructal Law: Optimization as Design Evolution

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Here, I review the physics meaning of optimization, knowledge and design evolution, and why these concepts and human activities are profoundly useful for human life. A law of physics is a concise statement that summarizes a phenomenon that occurs in nature. A phenomenon is a fact, circumstance, or experience that is apparent to the human senses and can be described. The design in nature phenomenon facilitates access for everything that flows, evolves, spreads, and is collected: river basins, atmospheric and ocean currents, animal life and migration, and technology (the evolution of the "human-and-machine species," wealth, life). This phenomenon is summarized by the constructal law: the occurrence and evolution of designs in nature, its time direction. Based on its record, the constructal law accounts for the design phenomenon and also for all the phenomena that have been described individually (ad-hoc) with end-design (destiny) statements of "optimality" (min, max). Most notably, the constructal law accounts for contradictory end-design statements such as minimum entropy production and maximum entropy production, and minimum flow resistance and maximum flow resistance.

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1 Optimization

Words have meaning, especially in science. One such word is optimization. Unfortunately, the meaning of this word has become blurred. Why is this, and why should we all care?

First, because to optimize is human, and, after we review the meaning of the word, we will recognize that to optimize is natural. Every moving thing does it freely, animate and inanimate. Every river alters its course and bed cross section to flow more easily. Every animal group varies its migration routes to facilitate its movement, i.e., its life. Every wounded tissue heals itself in order to keep the whole body moving, which means to keep the whole alive.

Second, optimization is the activity of making changes and choosing between the alternatives that emerge. To opt is to make a *choice*. It is a verb that came from Latin. To be able to choose, one must have the *freedom* to change the existing configuration (design, organization) and to choose from the alternate configurations that emerge after the change. To optimize is not a one-punch boxing match. It is a relentless fight. Why, because to find better choices after a change is "good." It is so good that it is addictive. The addiction reveals who we are.

Third, this human and natural tendency defines what good means. Good is the feature of the design that we make and select after every change. Good and design are concepts that belong in physics. They were placed firmly in physics as the law [1] (Fig. 1).

The three answers given above are worth contemplating, because science (like other old stories) has grown so long and complicated that the young do not know the meaning of some of the words they speak. The word "optimum" is a good example of this, because it is understood to mean "the best." In reality, the optimum is only the better choice from among the few choices that became available after one change. The best is short lived: precious today, replaceable tomorrow.

With freedom, new changes are made, more choices emerge, old bests die, and future bests are born. We see this truth every four years at the Olympics. This truth is the mother of all evolution.

Think of it in the opposite direction, to the absurd. What kind of science would that be where the choices made long ago are already "the best", and kept rigidly forever? It would be a senseless and useless science, with no future at all. It would be the opposite of the science that attracts us, inspires us, and empowers us on earth.

This is why a critical look at optimization is timely. To decipher the meaning of optimization as science we must come to terms with the phenomenon of design (organization) occurrence, change, evolution, and why this phenomenon is natural, universal (inanimate, animate, and human) and therefore profoundly useful.

2 Design Evolution, as Science

Design in nature has always been the main theme in science. It began with geometry and mechanics, which are about designs (configurations), their principles, and the contrivances made based on designs and principles. Science has always been about the human urge to make sense out of what we discern: numerous observations that we tend to store compactly as "phenomena" and, later, as much more compact "laws" that account individually for the phenomena. With science, we see farther ahead, we predict the future more accurately.

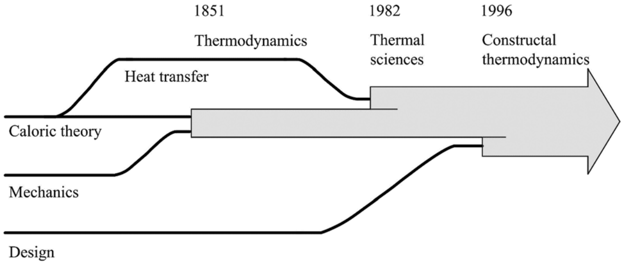

Fig. 1 The evolution and spreading of thermodynamics during the past two centuries (after Ref. 2, Diagram 1, p. 8)

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To see the position of design in nature as a subject in physics, it is necessary to recall that thermodynamics rests on two laws that are both "first principles." The first law commands the conservation of energy in any system. The second law commands the presence of irreversibility (i.e., the generation of entropy) in any system. The permanence and extreme generality of the two laws are consequences of the fact that in thermodynamics the "any system" is a black box. It is a region of space, or a collection of matter without specified shape and structure. The two laws are global statements about the balance or imbalance of the flows (mass, heat, and work) that flow into and out of the black box.

Nature is not made of boxes without configuration. The systems that we identify in nature have shape, structure, flow, and freedom to morph. They are resoundingly macroscopic, finite size, and recognizable as sharp lines drawn on a different background. They have organization, configurations, maps, and rhythms. The very fact that they have names (river basins, blood vessels, and trees) indicates that they have unmistakable appearances.

In the 1997 edition of my thermodynamics book [1], I pointed out that the laws of thermodynamics do not account completely for the systems of nature, even though scientists have built thermodynamics into thick books in which the two laws are just the introduction. The body of the doctrine is devoted to describing, designing, and "improving" things that seem to correspond to systems found in nature, or can be used by us to make human life easier. Nowhere is this more evident than in the method of entropy generation minimization [2,3] where design is recognized as "thermodynamics," even though neither of the two laws accounts for the natural occurrence of "design" and "design evolution" phenomena.

If physics is to account for the systems of nature, then thermodynamics must be strengthened with an additional self-standing law—with another first principle—that covers all phenomena of design occurrence and evolution. To achieve this, I added to physics the constructal law [1,4,5], which states (briefly) that "for a finite size system to persist in time (to live) its configuration must evolve such that it provides easier access to its currents."

The constructal law is a definition of life in the broadest possible sense: to be alive, a system must be able to flow and to morph freely in time so that its currents flow more and more easily. Live are all the animate and the inanimate systems that move and change configuration while moving. The constructal law commands that the changes in configuration must occur in a particular direction in time: toward designs that allow currents to flow more easily. The constructal law places the concepts of "better," design, and evolution centrally in physics.

The constructal law is a field that is expanding rapidly in physics, biology, technology, and social sciences. The field was reviewed regularly [6–9], and now it is expanding even more rapidly. No less than 13 books have been published on the constructal law since 2006 [10–22]. As of February 2015, the entry "constructal" on the Web of Science revealed an *h* index of 47 and a total number of 10,400 citations. On Google Scholar, the word "constructal" revealed 3500 published articles.

3 Design and Evolution: Law, Mechanism, and Impact

The constructal law of design in nature constitutes a unified view of design evolution. It predicts evolution in all the domains in which evolutionary phenomena are observed, recorded, and studied scientifically: animal design, river basins, turbulent flow, dendritic crystals, animal movement, athletics, engineering, technology evolution, and global design. Some of the most common and dissimilar animate and inanimate flow designs that we predicted with the constructal law are sketched in Fig. 2.

Evolution means design modifications, in time. The processes through which these changes are happening rely on mechanisms, and mechanism should not be confused with law. In the evolution of biological design, the mechanism is mutations, and biological selection. In geophysical design, the mechanism is soil erosion, rock dynamics, water–vegetation interaction, and wind drag. In sports evolution, the mechanism is training, recruitment, mentoring, selection, and rewards. In technology evolution, the mechanism is liberty, freedom to question, innovation, education, trade, theft, spying, and emigration.

What flows through a design that evolves is not nearly as special in physics as how the flow system generates its configuration in time. The "how" is the physics principle—the constructal law. The "what" are the mechanisms, and they are as diverse as the flow systems themselves. The what are many, and the how is one.

Having "impact" on the environment is synonymous with having flowing design and evolution. To flow means to get the surroundings out of the way. There is no part of nature that does not resist the flows and movements that attempt to get through it. Movement means penetration, and the name of this phenomenon differs depending on the direction from which the phenomenon is observed. To the observer of river basins, the phenomenon is the emergence and evolution of the dendritic vasculature. To the observer of the landscape, the phenomenon is erosion, and the reshaping of the earth's crust.

This mental viewing of design generation and environmental impact as a unitary phenomenon of physics is universally applicable. Think of the paths of animals, versus the river-like paths and burrows dug into the ground. Think of the migration of elephants, versus the toppling of trees. The patterns of social dynamics go hand-in-glove with impact on the environment.

Animal and human locomotion is "guided locomotion." It is movement with design—it is efficient, economical, safe, fast, foward looking, and purposefully straight. This is the constructal design of animal and human locomotion, and it is the complete opposite of Brownian motion. The constructal design of animal locomotion is much more complicated and perfected than the thermodynamics of balancing two work efforts, one on the vertical (lifting weight) and the other on the horizontal (getting the environment out of the way), which led to the purely theoretical prediction of the allometric relation between all animal speeds, body frequencies, and body mass [23–26].

The movement of the body weight on alternating legs is equivalent to viewing walking and running as a slender body that falls forward incompletely and repeatedly. The legs are the two spokes of the human wheel [27] from which the other spokes are missing, and which make the animal wheel the lightest wheel.

The constructal design of urban movement at length scales is such that the time needed to travel short and slow is roughly the same as the time needed to travel long and fast. The need to "travel short and long" to move on a territory (area, volume) was the example with which the constructal theory of design in nature began with two papers in 1996 [4,5]. This continued with explaining why the design of the Atlanta airport is efficient, and why the designs of new airports are evolving toward the Atlanta design [28,29].

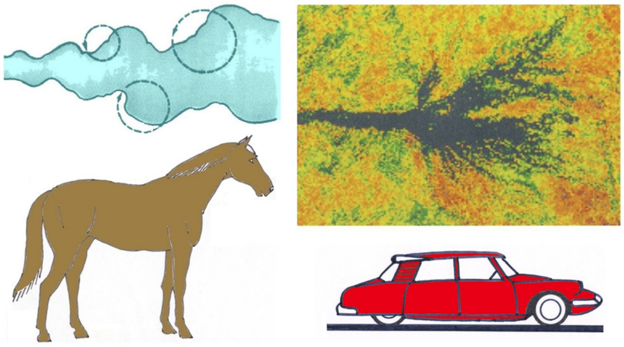

Fig. 2 The larger are more efficient, faster, live longer and travel farther lifetime: vehicles, animals, rivers, and the winds

In the Atlanta design, the short and slow is walking along the concourse, and the long and fast is riding on the train. In the city design, at the smallest scale, the time balance is between walking from the house to the car and riding on the small street. At the next scale, the balance is between riding on streets (short, slow) and avenues (long, fast), and so on to larger scales: avenues and highways, highways and intercity train and air travel, short flights and long flights, all the way to the scale of the globe. We have applied this principle to the design of the infrastructure (inhabited spaces) for fastest and safest evacuation of pedestrians, from crowded areas and volumes [30,31].

The slow and short are many, and the fast and long are few. The design of all movement on earth, animate and inanimate (river basins, eddies of turbulence, animal life, trucks on the roads, airplanes in the air, streets in the city) is one design: few large and many small, together [23,32].

The effect of life is measurable in terms of the mass moved over distances during the life time of the flow system (Fig. 3). The work required to move any mass on earth (vehicle, river water, and animal mass) scales as the weight of that mass time the distance to which it is moved horizontally, on the landscape. It is this way with the life of the river basin and the animal, and it is the same with the life of man, family, country, and empire. The economic activity of a country is all this movement—mass (people, goods) moved to distances. Because every movement is proportional to the amount of fuel burned in order to drive it, the entire economic activity on a territory must be proportional to the amount of fuel consumed on that territory. This view predicts that the annual gross domestic product (GDP) of a country should be proportional to the amount of fuel burned in the country (i.e., the useful energy generated and destroyed) [7]. This is confirmed by the economics data plotted in Fig. 4.

Animals have been spreading in space, in this unmistakable time direction dictated by the constructal law: from sea to land, and later from land to air [33]. The movement of the human and machine species evolved in the same direction, from small boats with oars on rivers and along the sea shore, to the wheel and vehicles on land, and most recently to aircraft.

The same movie (because this is what the occurrence and evolution of design is, a time sequence of images) shows that speeds have been increasing in time, and will continue to increase. For the same body mass, the runners are faster than the swimmers, and the fliers are faster than the runners. This movie is the same as the evolution of inanimate mass flows: under the persisting rain, all the river channels morph constantly, to flow more easily.

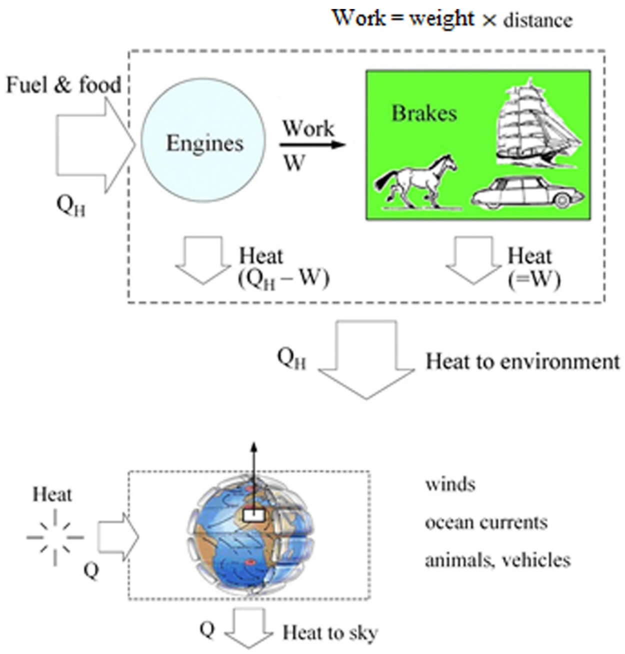

Fig. 3 Everything that moves on earth is driven by fuel and food. It moves because an engine dissipates its work output into a brake.

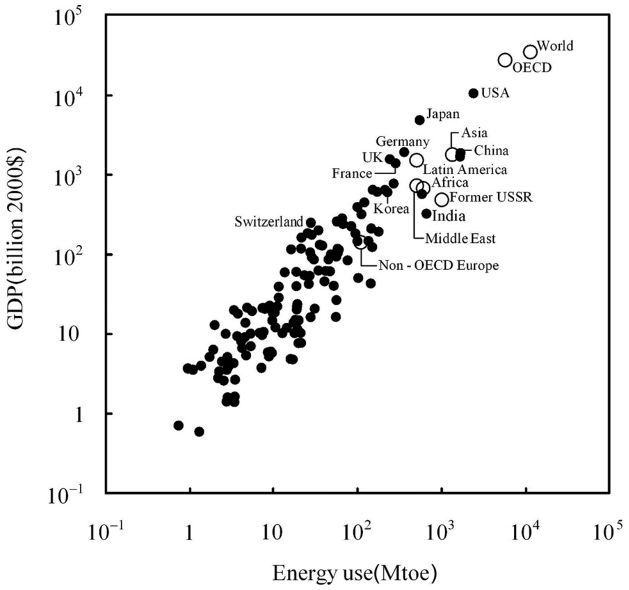

Fig. 4 Economic activity means movement, which comes from the burning of fuel for human needs. This is demonstrated by the annual GDP of countries all over the globe, which is proportional to the fuel burned in those countries (data from International Energy Agency. Key World Energy Statistics, 2006). In time, all the countries are moving up and to the right, on the bisector.

Spreading and collecting flows occupy areas and volumes that have S-shaped history curves predicted with the constructal law [34–36]. Design is the speed governor of nature. None of the changes observed in politics, history, sociology, animal speed, and river speed are spinning out of control. None of the expansions feared in geography, economics, and urbanism are slamming into a brick wall.

4 Constructal Law Versus Final Design

Final design ("the best") does not exist. The constructal law is not a principle of optimization, maximization, minimization, or any other static image of "end design" or "destiny." The constructal law is about the direction of evolution in time, and the fact that design in nature is not static: it is dynamic, ever changing, like the images in an endless movie. This is what design and evolution are in nature, and the constructal law captures them completely. Evolution never ends.

There have been many proposals of final design in science, but each addresses a narrow domain, and, as a consequence, the optimality statements that have emerged are self-contradictory, and the claim that each is a general principle is easy to refute. Here are some examples [9]:

(i) Minimum entropy generation and maximum efficiency are used commonly in engineering.
(ii) Maximum entropy generation is being invoked in geophysics.
(iii) Maximum "fitness" and "adaptability" (robustness and resilience) are used in biology.
(iv) Minimum flow resistance (fluid flow, heat transfer, and mass transfer) is invoked in engineering, river mechanics, and physiology.
(v) Maximum flow resistance is used regularly in physiology and engineering, e.g., maximum resistance to loss of body heat through animal hair and fur, or through the

insulation of power and refrigeration plants, the minimization of fluid leaks through the walls of ducts, and so on.

(vi) Minimum travel time is used in urban design, traffic, and transportation.
(vii) Minimum effort and cost is a core idea in social dynamics and animal design.
(viii) Maximum profit and utility is used in economics.
(ix) Maximum territory is used for rationalizing the spreading of living species, deltas in the desert, and empires.
(x) Uniform distribution of maximum stresses is used as an "axiom" in rationalizing the design of botanical trees and animal bones.
(xi) Maximum growth rate of flow disturbances (deformations) is invoked in the study of fluid flow disturbances and turbulence.
(xii) Maximum power was proposed in biology and is used in physics and engineering.

This list grows every time I compile it. Even though the optimality statements are contradictory, local, and disunited on the map of design in nature, they demonstrate that the interest in placing the design phenomena deterministically in science is old, broad, and thriving. One example is flow of stresses phenomenon [37,38] that accounts for the emergence of solid shape and structure in vegetation, skeleton design, and technology. The flow of stresses is an integral part of the design-generation phenomenon of moving mass more and more easily on the landscape (cf. Ref. 14, Ch. 10).

Another example is the contradiction between minimum and maximum of entropy generation (see (i) and (ii) above), which was resolved based on the constructal law in 2006 [28,39]. The flowing nature is composed of systems that move as engines connected to brakes that dissipate the work produced by the engines. In time, the "engines" of nature acquire configurations that flow more easily, and this means that they evolve toward less entropy generation, and more production of motive power per unit of useful energy (exergy) used. At the same time the "brakes" of nature destroy the produced power, and this translates into their evolution toward configurations that dissipate more and more power. The principle is not the maximum or the minimum, or the fact that the "engine + brake" construction of nature (Fig. 3) brings them together. The principle is the design evolution of "engine" configurations in the time direction dictated by the constructal law and the design evolution of brake configurations in the same direction over time.

To think that design evolution means "evolution toward patterns of least resistance" is, at best, a metaphor. Again, the meaning of words should be questioned (cf. Sec. 1). What "resistance" when walking in total freedom alone on the beach? What resistance when sitting down on the train in the Atlanta airport, and wanting to arrive at your gate faster? What resistance when searching for a cheaper ticket between Atlanta and Hong Kong? What resistance when the lucky animal finds food and we find oil? What resistance when the snowflake grows freely as a daisy wheel? What force drives all these flows that overcome resistances?

Furthermore, what is "least" (or maximum, or minimum) about any design? Who is to know that the urge to have an even better design has reached the end? Resistance is a concept from electricity (voltage divided by current), which was adopted subsequently in fluid mechanics (pressure difference divided by mass flow rate) and heat transfer (temperature difference divided by heat current). In pedestrian and animal movement the current is obvious: it is the flow rate of human mass through a plane perpendicular to the flow path. Not obvious is the "difference" (voltage, pressure, and temperature) that drives the pedestrian flow.

I faced these questions squarely when I formulated the constructal law in 1996 [1,4,5], and this is why I summarized *intentionally* the design in nature phenomenon with a statement of all physics that is universally applicable, without words such as resistance and static end-design (optimum, min, and max). Yet, in our morphing movement (i.e., life) on earth, we rely on thoughts such as greater access, more freedom, go with the flow, shorter path, less resistance, longer life, less expensive, and greater wealth. These ideas guide us, like the innate urges to have comfort, beauty, and pleasure.

The constructal law empowers the mind to fast-forward the design evolution of the human-and-machine species. This is in fact what the human mind does with any law of physics—the mind uses the law to predict features of future phenomena. Knowing ahead is also a manifestation of the constructal law [33], because all animal design is about moving more and more easily on the landscape, and this includes the phenomenon of cognition—the urge to get smarter, understand, and remember faster, so that the animal can get going and place itself out of danger. Relying on the constructal law direction to fast-forward the design is useful.

5 Technology Evolution

Based on its record [6–9], the constructal law is the law of physics that accounts for design in nature in animate, inanimate, and social flow systems. Technology evolution [40] is just one class of design-in-nature phenomena, and it is no different than animal evolution, river basin evolution, science evolution, or any other kind of evolution. To see this, consider Fig. 5. A vehicle consumes fuel and moves on the world map. We ask how large one of the components of this vehicle should be, for example, a duct with fluid flowing through it, or a heat exchanger surface. Because the size of the component is finite, the vehicle is penalized (in fuel terms) by the component in two ways.

First, the component is a flow system that operates irreversibly, with entropy generation, which means the destruction of useful energy (the consumed fuel), because of currents that flow by overcoming resistances, obstacles, and all kinds of "friction." This fuel penalty is smaller when the component is larger, with wider ducts and larger heat transfer surfaces. In this limit, larger is better, because the component poses less resistance to the flow of fluid, heat, mass, and stresses [14,41].

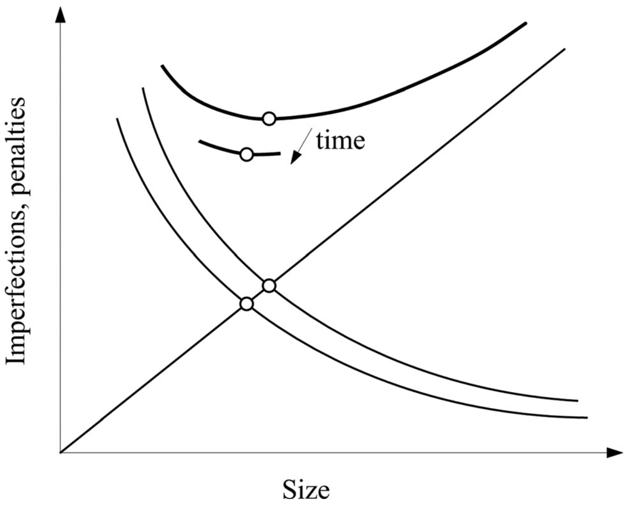

Fig. 5 **Large organs belong on large vehicles and animals. Every flow component has a characteristic size, which emerges from two conflicting trends. The useful energy dissipated because of the imperfection of the component decreases as the component size increases. The useful energy spent by the greater system (vehicle, animal) increases with the component size. The sum of the two penalties is minimum when the component size is finite, at the intersection between the two penalties. In time, the component evolves toward smaller sizes, because it improves and its penalty (the descending curve) slides downward.**

Second, the vehicle must burn fuel in order to transport the component. The fuel penalty for the component is proportional to the weight of the component and teaches that smaller is better. This second penalty is in conflict with the first, and from this conflict emerges the notion—the prediction, the purely theoretical discovery—that the component should have a characteristic size that is finite, not too large, not too small, but just right, for that particular vehicle. At bottom, the total fuel required by the vehicle is proportional to the total weight of the components.

The two penalties are the two asymptotes drawn in Fig. 5. The sum of the two penalties is minimal when the component size is essentially the same as the size obtained by intersecting the asymptotes. Locating the design (the component size) in this fashion is one of the more recent examples of the application of *the method of intersecting the asymptotes*, which is being developed from edition to edition since 1984 in my convection book [42,43]. "Characteristic size" means that large components (pipes, heat exchangers, etc.) belong on large vehicles, and small components belong on small vehicles. It also means that *all components are imperfect*, because each has a finite size, not an infinite size.

The whole (the vehicle) is a construct of "imperfect" components. Perfection at the component level is not god for performance at the global level. The vehicle design evolves in accord with the constructal law, as it becomes a better and better construct for moving the vehicle mass on the world map. Here, better means moving more mass farther per unit of fuel consumed.

Everything that we can say about vehicles in relation to Fig. 5 applies to animal organs and the whole animal. Every organ must have a certain, characteristic size, which is larger when the animal is larger. Every organ is imperfect thermodynamically because of its finite size. The animal is an evolving organization of imperfect interconnected organs.

The crucial difference between the animal and the vehicle, or between the heart and the water pump, is that we cannot witness animal evolution because it occurred over an enormously long time interval. We can, however, witness sports evolution and technology evolution. In fact, the time scale of technology evolution is so short that most of what enables our movement on the map evolved during the past one hundred years: central power plants, electrification, the automobile, and the airplane.

In time, the organ evolves toward designs that flow more easily. This means that in Fig. 5 the descending curve migrates downward over time, and so does its intersection with the rising line. The minimum of the aggregate penalty curve follows suit, and migrates downward and to the left. The discovery is not only that the future component must be better in an evolutionary manner, but also that it must be smaller. The constructal law calls for the future, and the name for this future is miniaturization.

Now we know why miniaturization should happen. It is the natural tendency in each of us to move our body, vehicle, and clan more easily and for longer time and space on the world map. In thermal engineering, miniaturization happens, and it did not start with nanotechnology. Before nanotechnology we had microelectronics, and before microelectronics we had compact heat exchangers.

The evolution toward greater density of volumetric flow, or functionality, is another way to describe the evolution of technology for easier human-and-machine movement on earth. The reason is that no matter how small the smallest flow features become (e.g., from micro to nano), the new devices that empower the human-and-machine species must continue to match the length scale of the human body. The smaller the smallest features, the more numerous are the tiniest components of the new device. These tiny flow systems are not poured into the human-and-machine specimen, like beans in a sack. They must be assembled, connected and constructed (organized) to flow together so that they bathe the available "whole" completely.

The march toward miniaturization is necessarily an evolution toward easier volumetric flow architectures that are more complex because their smallest features become smaller and more numerous. The fascination with the nanophenomenon, the nanoelement and the nanoperformance misses the big picture, which is the construction of the *macrodevice* (e.g., lung) that relies on clever elements at the smallest scale and in the largest numbers (e.g., alveoli).

The discovery of the construction is delivered by the constructal law, after invoking it for the flow of the whole. This is illustrated in Fig. 6, which is a review of three decades of research on the cooling of electronics packaged on parallel plates in a volume of finite size [14,43]. The length scale of this volume, L, can vary, and has been varying over time. Think of the evolution of electronics, from phone booths, to servers and laptops and hand-held devices today.

Three cooling technologies are summarized in Fig. 6: natural convection (NC), forced convection (FC), and solid body conduction (C). The chronological sequence in which these technologies emerged and spread is NC–FC–C, because this is the sequence in which greater density is achieved faster. These changes should not end: C is not an "end design," i.e., not an ultimate technology. The stepwise evolution continues, for example, from Fourier conduction cooling (C) to conduction at nano scales.

Conduction cooling with high-conductivity tree-shaped inserts was not discovered with the constructal law. It happened the other way around [4]: the constructal law was discovered in the conduction cooling designs.

There are several classes of flow configurations in nature, and each class can be derived from the constructal law in several ways: analytically or numerically, approximately or more accurately, blindly (random search) or using strategy (shortcuts), and so on. Classes that our group treated in detail, and by several methods, are the cross-sectional shapes of ducts, the cross-sectional shapes of rivers, internal spacings, and tree-shaped architectures in animate and inanimate flow systems.

Tree architectures were treated by us not as "models" but as fundamental problems of access to flow: volume to point (e.g., exhaling), area-to-point (e.g., river basin), line to point (e.g., electronics cooling), and the respective reverse flow directions. Important is the geometric notion that the "volume," the "area," and the "line" represent *infinities* of points.

The theoretical discovery of flowing trees (in Refs. [4,5], and later) came from the decision to connect one point (source, or sink) with an *infinity* of points our tree-shaped flow architectures was based on three approaches. It started in 1996 with an analytical shortcut [4,5] based on several simplifying assumptions: 90 deg angles between stem and tributaries, constant-thickness branches, a construction sequence in which smaller optimized

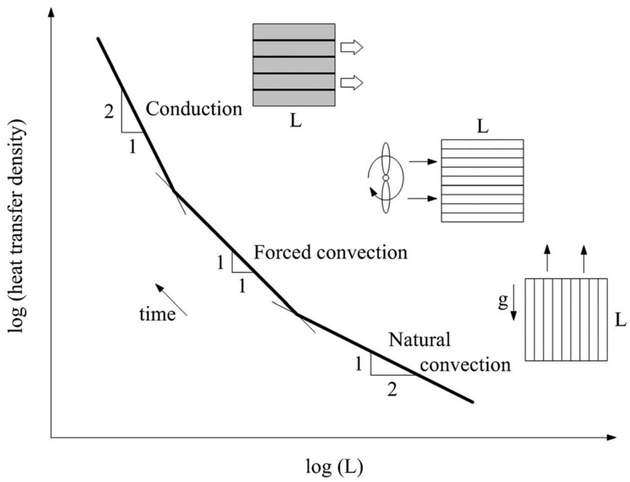

Fig. 6 Predicted evolution of heat transfer density toward higher values, showing two phenomena: evolution toward smaller sizes (miniaturization), and stepwise changes in cooling technology

constructs are retained, and so on. Months later, we solved the same problem numerically [44] by abandoning most of the simplifying assumptions (e.g., the compounding construction sequence) used in the first papers. In 1998, we reconsidered the problem in an area-point flow domain with randomly moving low-resistivity blocks embedded in a high-resistivity background ([45], available also in Refs. [24,28]) with Darcy flow, that is with permeability instead of conductivity, Fig. 7. Grains of high-resistivity were identified and replaced with grains of low-resistivity in such a way that the global resistance of the area-to-point flow decreased in every frame of the evolutionary design. Along the way, we found better performance and trees that look more "natural" as we progress in time; that is, as we endowed the flow structure with more freedom to morph. Figure 8 shows the most recent tree design for conduction in a heat generating medium with high-conductivity channels that are the most free to morph [46].

Darcy fluid flow is one form of "diffusion," i.e., the same physics phenomenon as thermal diffusion (Fourier conduction) and electrical diffusion (Ohm conduction). Yet, a disturbing trend has emerged in publishing: it is to copy the original work, change a few key words (i.e., "translate"), and publish the same idea brazenly as "new" after replacing the Darcy diffusion language with thermal diffusion language (as Guo et al. [47] have done). Critiques of Guo et al. [47] were just published independently by seven groups of authors [48–54], who showed that the concept of "entransy" is false and not useful.

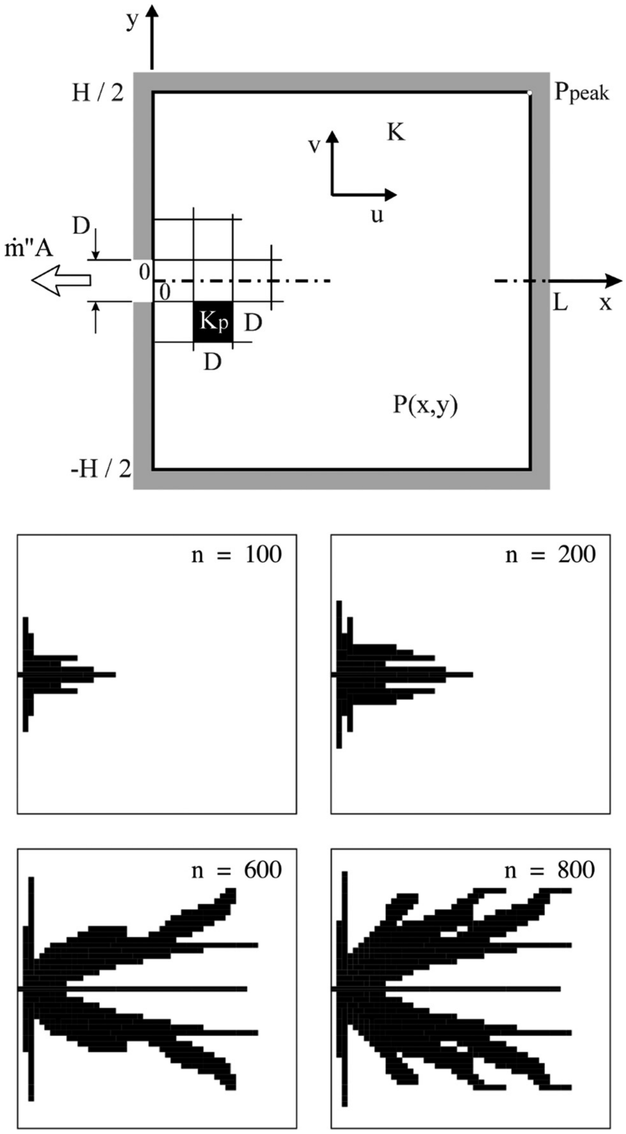

Fig. 7 Darcy flow on a square domain with low permeability (*K*) and high permeability (K_p). In time, *K* grains are searched and replaced by K_p grains such that the overall area-to-point flow access is increased faster ([45], available also in Refs. [24,28]).

6 Constructal Thermodynamics

The constructal law is universally valid, as physics, precisely because it is not a statement of static optimality and final design (all the optimization statements have failed: see again (i)–(xii) in Sec. 4). A new law does not have to be stated in mathematical terms (e.g., thermodynamic variables, units). For example, the second law of thermodynamics was stated in words, as a mental viewing, not as a mathematical formula (see the Clausius and Kelvin statements [1]). The mathematization of the second law statement (and of thermodynamics) came later. The same evolution occurred in constructal theory. The 1996 statement of the constructal law was followed in 2004 by a complete mathematical formulation of constructal law thermodynamics [55], Fig. 1.

The constructal law unites physics and biology because it simplifies and clarifies the terminology that is in use, and it justifies the biology-inspired terminology that is in use in many other fields such as geophysics, economics, technology, education and science, books, and libraries [56]. This unifying power is both useful and potentially controversial because it runs against current dogma.

For example, the constructal designs of the river basin, the tree distribution in the forest, the animal distribution and "animal flow" on the landscape, and all the other "few large and many small" designs such as the food chain, demography, and transportation are viewed as whole architectures in which what matters is the better and better flow over the global system. In all such architectures, the few large and many small flow together. They collaborate, adjust, and collaborate again toward a better flowing whole, which is better for each subsystem of the whole. This holistic view of design phenomena represents two new steps:

First, the concept of better is defined in physics terms, along with direction, design, and evolution (cf. the constructal law). In biology, this step unveils the concept of random events and mutations ("changes," from this to that, from here to there) as a mechanism akin to river bed erosion, periodic food scarcity, plagues, scientific discovery, etc., which make possible running sequences of changes that are recognized widely as evolution. This step places in physics the biology terms of natural selection, freedom to change and adapt, survival, and the idea that there are better designs.

Second, the constructal view of design and evolution runs against the negative tone of biology-inspired terms that have invaded the scientific landscape, for example, winners and losers, zero sum game, competition, hierarchy, food chain, and limits to growth. No, in the big picture the few large and many small evolve and flow together, in order to be able to move more mass on the landscape farther and longer in time, i.e., to survive. The few large do not and cannot eliminate the many small. Their balanced multiscale design gets better and better, for the benefit of the whole flowing system. Contrary to this apparent conflict with standard interpretations of evolutionary biology, what is good in biology is good in constructal thermodynamics and all the domains of design science that the constructal law covers.

The constructal law is predictive, not descriptive. This is the big difference between the constructal law and other views of design in nature. Previous attempts to explain design in nature are based on empiricism: observing first and explaining after. They are backward looking, static, descriptive and at best explanatory. They are not predictive theories even though some are called "theory," e.g., complexity theory, network theory, chaos theory, power laws (allometric scaling rules), "general models," and

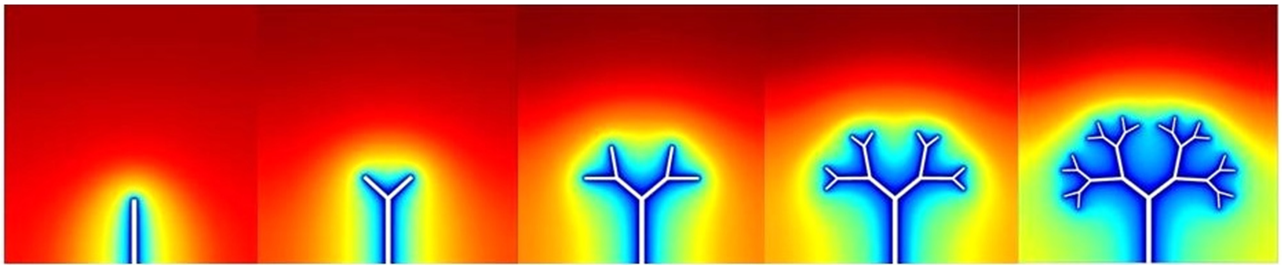

Fig. 8 Constructal invasion of a conducting tree into a conducting body [46]

optimality statements (minimum, maximum, and optimum). Models are acts of empiricism, not theory.

With the constructal law, complexity and scaling rules are discovered, not observed. Complexity is finite (modest), and is part of the description of the constructal design that emerges. If the flows are between points and areas or volumes, the constructal designs that are discovered are tree-shaped networks. The "networks" are discovered, not observed, and not postulated. Networks, scaling rules, and complexity are part of the description of the world of constructal design that emerges predictively from the constructal law.

Constructal "theory" is not the same as constructal "law." Constructal theory is the view that the constructal law is correct and reliable in a predictive sense in a particular flow system. For example, reliance on the constructal law to predict the evolving architecture of the snowflake is the constructal theory of rapid solidification. Using the constructal law to predict the architecture of the lung and the rhythm of inhaling and exhaling is the constructal theory of respiration.

The law is one, and the theories are many—as many as the phenomena that the thinker wishes to predict by invoking the law.

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