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Science and technology as evolving flow architectures

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SUMMARY

This essay traces the evolution of thermodynamics from its origins to *ad hoc* applications of thermodynamic optimization (entropy generation minimization) and the principle-based generation of flow configuration in nonequilibrium systems (constructal theory). Geophysical and biological flow systems evolve in one direction, toward configurations that flow more easily. This evolutionary process is like an animated movie in which existing flow designs are replaced by designs that offer greater flow access. This paradigm fuels a new attitude toward globalization and sustainability: the natural way to bring the less advanced areas into the flow of things is to allow the vascular systems of goods, people and ideas to bathe the whole earth more and more freely. Constructal theory shows that freedom is good for design, and that the future belongs to vascularized architectures with increased svelteness and optimal distribution of imperfection. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: constructal; evolution; science; technology; history; sustainability; globalization; civilization; energy future

1. A NEW ATTITUDE TOWARD GLOBALIZATION AND SUSTAINABILITY

'People in advanced countries consume too much energy'. We hear such statements daily. In the debate on how to build a better and 'more sustainable' energy future for the developed and developing world, the implications are intended to be obvious. One is that advanced countries by consuming less energy, will and should leave more fuel to the less advanced countries to burn. Another is that burning fuel, in any case, is inherently bad, like smoking or gluttony. Fuel abstinence or at the very least a 'low calorie' diet is the solution.

Is the world really foolhardy to have arrived at this level of civilization by consuming 'too much' energy? By taking a look at basic physics and the history of societal organization and global development, we can examine this question without bias.

'Energy production' means the shaft work produced by a heat engine or a power plant. Throughout most of our history, work was produced by people and animals, with minor medieval contributions from windmills and water wheels. The big change in the evolution of humans was the development of heat engines in the 1700s, followed by the rapid industrialization of the

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western world in the 1800s and the electrification of the globe in the 1900s. This global flow of technology continues, and it defines us today.

In its simplest description, the work that a power plant delivers per unit time (the power) is proportional to the rate of heating that the plant receives from the burning fuel. The delivered power output can be mechanical, as through a turning shaft, or electrical through cables. The delivered power is proportional to the rate at which fuel is consumed times the efficiency of the power plant. For power, we need fuel use and efficiency. Both have been increasing in time (Figure 1). This evolution continues.

This is completely analogous to what occurs on a much greater and diverse scale in animal design. The mechanical power delivered by muscles is proportional to the rate of food consumption (the metabolic rate). This analogy casts humans in a different light on the stage of evolution: we are 'human and machine species', evolving in visible terms (right now) because our minds and engineered extensions (machines, technologies) are evolving. We are a lot bigger, a lot more complicated, and a lot more powerful than the naked bodies shown in anatomy books.

Why do humans need power? For the same reason that animals need muscle power: to move mass on the earth's surface. Recent theoretical work on the origins of animal locomotion [4,5] has shown that for all types of locomotion (running, flying, swimming), animal force is roughly equal to the body weight, and the minimum work that the body performs is proportional to the body weight times the distance traveled. The consumed food or fuel is 'converted' into mass moved.

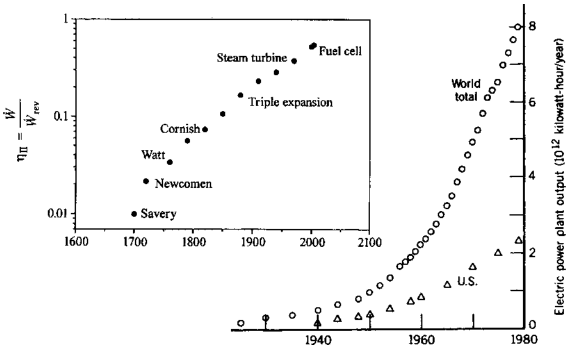

Figure 1. Time evolution of the second law efficiency of power plants, and the growth of power generation world wide ([1]; efficiency data from [2]; power generation data from [3]).

Our cars, construction sites, and everything else we do (our legacy) are the product of this. All the animals and all of us consume food and fuel and the result is the shaping and reshaping (the mixing) of the earth's surface.

Now we can address the question posed at the start. People in advanced countries burn more fuel per capita than people in less advanced countries. Why? Because the flow of mass on the earth's surface is distributed nonuniformly. 'Advanced' means just that, more mass moved over longer distances, along *certain* channels. The flow map has history and memory. In time, new channels appear and the old ones become thicker (Figures 2 and 3).

To argue for a more uniform distribution of fuel consumption is to recommend a more uniform distribution of mass movement (goods, people, information) on the globe. This sounds progressive, but even a global government would be hard pressed to achieve it.

Our movement and animal locomotion is mass that flows on the earth with the same tendency as that of water in a river basin. The tendency is to generate *in time* configurations that make it easier to flow. This natural evolutionary phenomenon is what the constructal law covers. The configuring of the flow structure means *the optimal distribution of imperfection*: flow resistances, obstacles, bottlenecks, and choke points, all in the right amounts and in the right places on the map. The winning blueprint—the flow pattern that survives in time—is the communal allocation of flow resistances (channels) to areas without channels.

The striking feature of winning designs in nature is their *nonuniform* distribution of channel sizes and flow rates. The river basin is a tree, a flow design with very few big channels and very many small channels. The urge of the smallest is the same as the urge of the biggest: the urge is to flow

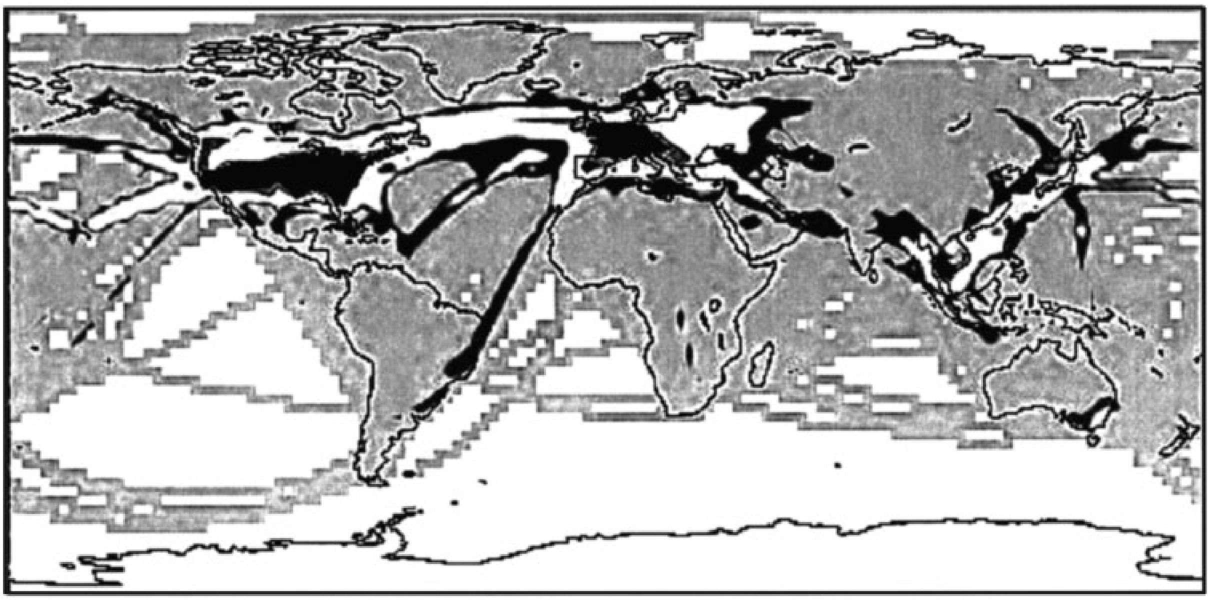

Figure 2. Where aircraft flew in 1992 and the persistent contrail coverage (in % area cover) for the 1992 aviation fleet (from [6]). See also [7].

Figure 3. Where aircraft will fly in 2050 and the persistent contrail coverage (in % area cover) based on meteorological analysis data and on fuel emission database for 2050 (from [6]). See also [7].

more easily. This is why all sizes come together into a tree-shaped vascularized tissue. This is why European integration and globalization are *natural* occurrences.

How should we proceed? Clearly, not by fighting nature. The nonuniform distribution of power generation and use will continue to happen. Needed is a new attitude toward globalization and

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sustainability. For this, the river basin and the rail and highway networks are excellent metaphors.

The natural way to bring the less advanced areas into the flow of things is to *allow* the river basins of goods, people, and information to bathe the whole earth more and more freely. Constructal theory has shown that *freedom is good for design*. These freely changing flow configurations are what will attach the overlooked areas to the big branches. This natural phenomenon should be recognized, so that policy makers may make the right decisions faster.

2. THE EVOLUTION OF TECHNOLOGY

Times change, generations replace generations, but the principles remain. Contrivances, gadgets, and fads are just the opposite. They parade in front of our eyes, but their impact on the 'thin book' of fundamentals is nil.

I was reminded of this last semester because of a wonderful coincidence called 'serendipity'—the road to important but unintended discoveries when the traveler has his eyes open. For science, serendipity is the kitchen, the storeroom, and the cook. I was at The National Conservatory of Arts and Professions (CNAM), in Paris. CNAM has a 300-year old edifice with towers, inner court, statues, clocks, and history chiseled in stone. In the front court, there is the statue of Denis Papin and the first piston and cylinder machine that expanded steam to produce work (1690). This was before the engine builders of Britain and 80 years before James Watt.

Around the buildings, and around the ceilings of the oldest and most decorated classrooms, are the names of those who left their mark. One is Sadi Carnot. Without it there would be no thermodynamics, power engineering, and standard of living as we know them today. Sadi Carnot came to CNAM to contemplate, to think in quiet about the army of contrivances that was invading France: the steam engines. The industrial revolution was on the march. Britain had industrialized itself in the 1700s. A century later, it was the turn of the continent to do the same.

Why were the steam engines invading? Because their effect on people's lives was good. It was dramatic. Engines were empowering people. They were liberating slaves, serfs, and animals. They were facilitating the movement of humanity all over the globe.

The principle that Sadi Carnot saw in that parade of machines is that every thing flows one way, from high to low. This is the one-way direction—the time arrow—of irreversibility. Water flows through a pipe from high pressure to low pressure. Heat flows from high temperature to low temperature. Water falls from high to low through a water wheel. This principle is known today as the second law of thermodynamics, irreversibility, dissipation, inefficiency, one way, 'water under the bridge', etc. Today, this is thermodynamics, the science of everything that kicks and moves.

The new principle that the CNAM story illustrates for us today is the principle of *evolution of design* (e.g. Figure 1). The flow configurations (the engine designs) compete, and the designs that flow 'more easily' are the ones that survive. The human and machine species evolves, and its evolution shows 'live' how all other flow systems have evolved, from geophysics to biology and social organization on the globe. In this constructal direction of time the flow configurations become more efficient, more compact (svelte), and cover larger spaces [8–10]. This principle is the constructal law:

> For a finite-size flow system to persist in time (to survive) its configuration must evolve such that it provides greater and greater access to the currents that flow through it [11,12].

Both principles are in action, the second law and the constructal law. Their footprints persist, like the river beds and the beaten tracks. The river and the caravan that do not follow their beds and beaten tracks do not get far. The engineer who does not recognize the two principles lives in the prethermodynamics era (in mechanics) and does not get far either.

3. FROM ENTROPY GENERATION MINIMIZATION TO CONSTRUCTAL THEORY

The improvements summarized in Figure 1 happened because 10 generations of designers and builders have done their best to minimize 'losses'. Sadi Carnot wrote about the importance of avoiding friction and heat transfer across finite temperature differences, however, common sense (the urge to live better) lead the human and machine species in the direction of Figure 1 anyway.

Carnot identified the principle that one generation later became the second law, and in this way he kick-started thermodynamics as a science distinct from mechanics. The history of thermodynamics is not the subject of this section. The subject is the observation that after being educated in the use of the first law and the second law, engineers have always sought to *improve* the global performance of the power plant or refrigeration plant. They used thermodynamics, and they accomplished great things with it. Yet, there was nothing in the laws of thermodynamics to indicate that the global performance of flow systems must increase in time.

This observation surprises many and with good reason. The observation has been around us, everywhere and forever. That design exists and improves in time has been taken for granted. The hardest things for us to question are the most common and the most obvious.

We thermodynamicists have expanded the language and techniques of our discipline in order to make it easier for engineers to improve their machines. The losses that Carnot warned against became 'irreversibility', 'entropy generation' ($\dot{S}_{\text{gen}}$) and 'exergy destruction'. That these thermodynamics-sounding names represent 'losses' was formalized in the Gouy–Stodola *theorem*,

$$\dot{W}_{\text{rev}} - \dot{W} = T_0 \dot{S}_{\text{gen}} \tag{1}$$

The name 'theorem' is correct, because Equation (1) is derived by combining the first law with the second law. To calculate the loss ($\dot{W}_{\text{rev}} - \dot{W}$, or $\dot{S}_{\text{gen}}$) is to perform 'second law analysis', 'exergy analysis', 'entropy generation analysis', etc. The configuration of the thermodynamic system is assumed given. As shown in Figure 4 at the volumetric level, and in Figure 5 at the macroscopic level, this 'combined-laws' analysis indicates *where* losses occur and how large they are.

To *minimize* losses is a different concept. There is nothing in the laws of thermodynamics to require that ($\dot{W}_{\text{rev}} - \dot{W}$) or $\dot{S}_{\text{gen}}$ must be decreased by us, nature or anybody else. In spite of this theoretical vacuum, our discipline marched forward and developed methods and strategies for minimizing losses. It marched in time because this is the direction of better science (Section 5). Science rushes forward even when the necessary 'new' concepts, words, and laws are not available. To make real progress in these early stages, scientists *misuse* the existing language [14].

My way of identifying and minimizing losses is the method of *entropy generation minimization* (EGM), which has its origins in my doctoral thesis

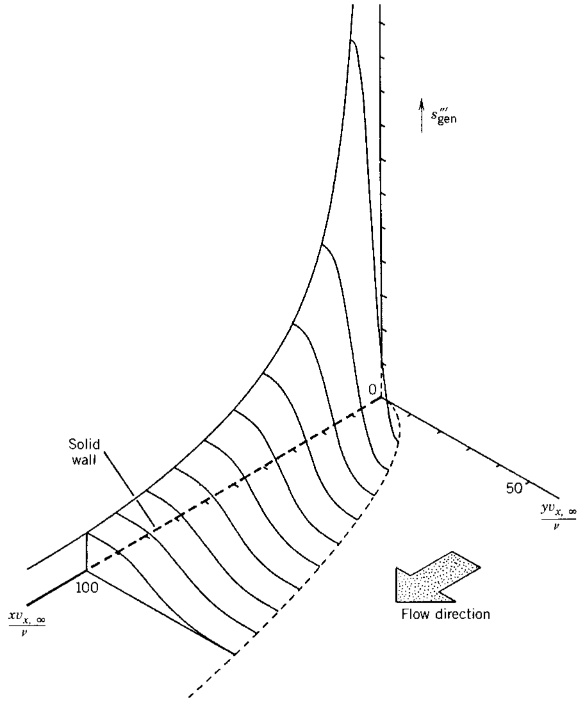

Figure 4. Volumetric s'''_{gen} distribution of entropy generation rate in a laminar boundary layer flow on a plane wall with heat transfer. The wall is at $y = 0$. The boundary layer is sketched in the bottom plane [13].

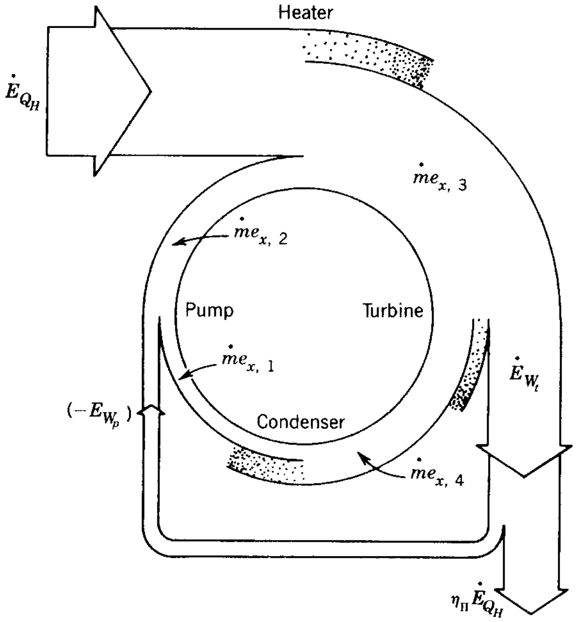

Figure 5. *Exergy wheel* diagram for a power plant with simple Rankine cycle [12].

at MIT—in a series of papers that began with [15] and led to my first Wiley book [16]. Note here that the decision to minimize S_{gen} was arbitrary. Thermodynamics did not give me that right.

Constructal theory is a mental viewing that I had about 10 years ago. I saw that by optimizing globally a flow system, I was minimizing thermal and fluid-flow resistances *together*. I was balancing them so that their sum is minimum. I was not minimizing them individually, and I was certainly not eliminating them. I was not aiming for the Carnot limit. The flow system was destined to remain imperfect. I was like an artist, attempting to paint *the least imperfect* fresco possible.

In the mid-1990s I came to the realization that all this effort meant that I was *generating flow geometry*. I was discovering the drawing (the design), that is, the configuration for a flow system (nonequilibrium system, in thermodynamics) that did not have configuration. The generation of configuration is a universally present phenomenon, which did not have a universal underlying principle in physics. The generation of flow configuration is the phenomenon responsible for the morphology and evolution of natural flow systems (animate and inanimate) and engineered systems.

It became clear that one does not need the word *entropy* to state the principle of evolution of the flow configuration in time. That principle is a new law of physics—the *constructal law* stated in Section 2. Configuration is the footprint—the fossil, the evidence of a tendency in time: flow systems seek and find configurations that provide progressively greater access to their currents. Existing flow configurations are replaced by better flowing configurations, smoothly or stepwise, in animal design, river basin design, automobile design, and geopolitical design.

The time arrow of the constructal law is not to be confused with the time arrow of the second law. The second law is the law of entropy generation, whereas the constructal law is the law of configuration generation. The concept defined by the second law is entropy. The concept defined by the constructal law is evolution of configuration (design, pattern, layout, drawing).

4. THE ANIMATED MOVIE OF CONFIGURATION GENERATION

To see why the constructal law is a law of physics, ask why the constructal law is different than (i.e. distinct from or complementary to) the other laws of thermodynamics, think of an isolated thermodynamic system that is initially in a state of internal nonuniformity (e.g. regions of higher and lower pressures or temperature, separated by internal partitions that suddenly break). The first and second laws account for numerous observations that describe a tendency in time, a time arrow: if enough time passes, the isolated system settles into a state of equilibrium (no internal flows, maximum entropy at constant energy, etc.). The first and second laws speak of a black box. They say nothing about the configurations (the drawings) of the things that flow. Classical thermodynamics was not concerned with the configurations of nonequilibrium (flow) systems.

This tendency, this time sequence of drawings that the flow system exhibits as it evolves, is the phenomenon covered by the constructal law: not the drawings *per se*, but the time direction in which they morph if given freedom. No drawing in nature is 'predetermined' or 'destined' to be or to become a particular image. The actual evolution or lack of evolution (rigidity) of the drawing depends on many factors, which are mostly random (Figure 6). One cannot count on having the freedom to morph in peace (undisturbed).

Once again, a comparison with the second law is revealing. No isolated system in nature is predetermined or destined to end up in a state of uniform intensive properties so that all future flows are ruled out. One cannot count on the removal of all the internal constraints. One can count even less on anything being left in peace, in isolation.

The second law does proclaim the existence of a 'final' state: the concept of equilibrium in an isolated system, at sufficiently long times. Similarly, the constructal law proclaims the existence of a final nonequilibrium (flow) state: the concept of the *equilibrium flow architecture* [8,9], when all possibilities of increasing morphing freedom and flow performance have been exhausted.

Constructal theory is now a fast-growing field with contributions from many sources, which have been reviewed on several occasions [7,10,19–25]. This new body of literature is not reviewed here. In this section I sketch a balance between the original disclosure of the theory and the newer developments. Striking a balance is a welcome opportunity to reflect, because during the 10 years that passed, we questioned the earliest work and improved the results, drawings, and language. The

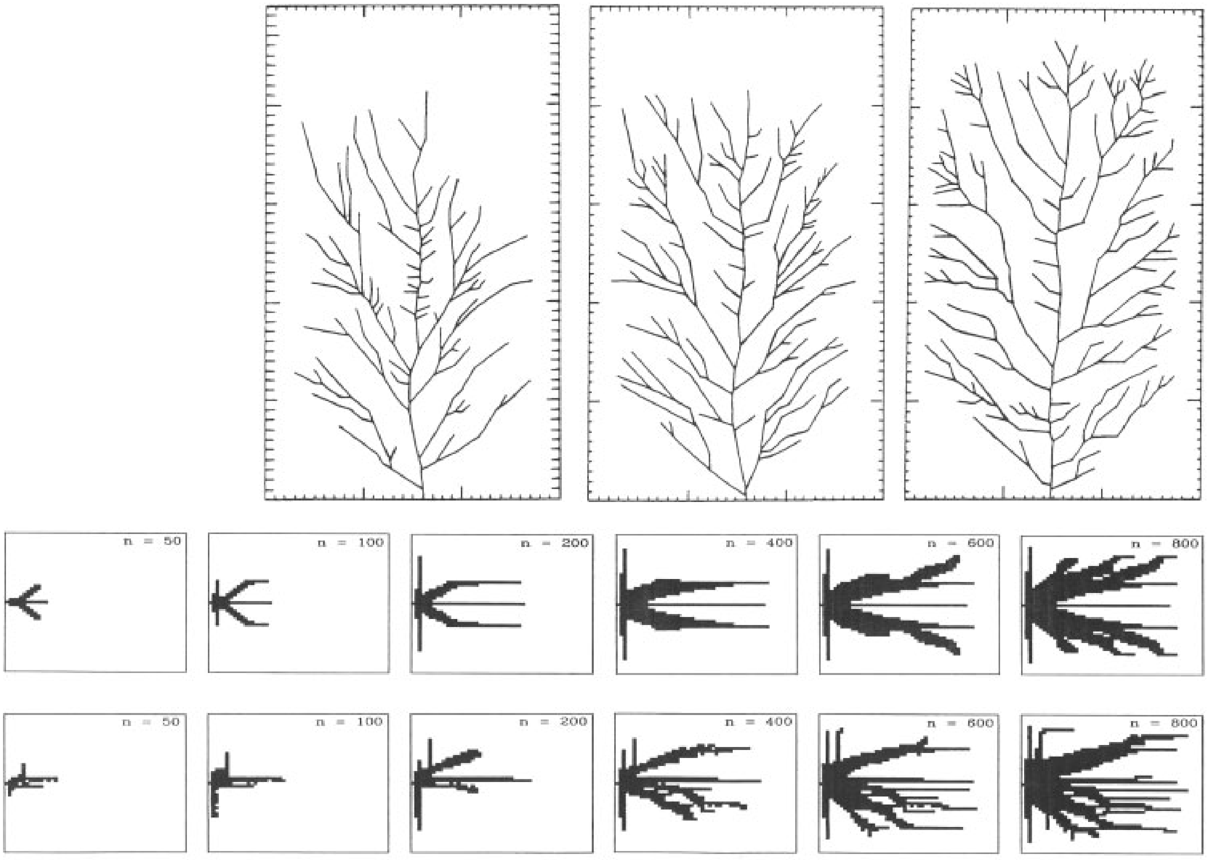

Figure 6. Top: Development of an artificial river basin over a $15.2 \times 9.1\,\mathrm{m}^2$ rainfall erosion area [17]; Bottom: Simulations based on an erosion model with uniform erosion resistance, and random erosion resistance [18].

bottom line, however, is that constructal theory is the 1996 law cited in Section 2 of this article. The constructal law statement is general; it does not use words such as *tree*, *complex versus simple*, or *natural versus engineered*.

In retrospect, I find that it is important for readers not to confuse the constructal law with predictive applications of the idea in various domains. How to deduce a class of flow configurations by invoking the constructal law is an entirely different (separate, subsequent) thought, which in my teaching effort is called the researcher's *freedom to choose* the problem and solution method [26]. There are several classes of flow configurations, and each class can be derived from the constructal law in several ways: analytically (pencil and paper) or numerically, approximately or more accurately, blindly (random search) or using intelligence (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.

For example, to discover 'trees' our group treated them not as models (many have published and continue to publish models) but as fundamental access-maximization problems: volume to point, area to point, line to point, and the respective reverse flow directions. Important is the elementary geometry notion that the 'volume', the 'area', and the 'line' represent infinities of point. Our theoretical discovery of trees stems from the decision to connect one point (source, or sink) with an *infinity* of points (volume, area, line). It is the reality of the continuum (the infinity of points) that is routinely discarded by modelers who approximate the space as a finite number of discrete points and then cover the space with drawings made out of 'sticks', which (of course) cover the space incompletely (and from this fractal geometry). Recognition of the continuum requires a study of the interstitial spaces between the tree links. The interstices can only be bathed by high-resistivity diffusion (an invisible, disorganized flow), whereas the tree links serve as conduits for low-resistivity organized flow (visible streams, ducts).

The two modes of flowing with thermodynamic imperfection, the interstices and the links, must be *balanced* so that together they contribute minimum imperfection to the global flow architecture. The flow architecture is the graphical expression of the balance between links and their interstices. The deduced architecture (tree, duct shape, spacing, etc) is the *optimal distribution of imperfection*. Those who model natural tree-shaped flows and do not optimize the layout of every black line on its allocated white patch, miss the drawing. The white is as important as the black.

For tree-shaped flow architectures we used three approaches. In 1996, I started with an analytical pencil and paper method based on several simplifying assumptions: rectangular elements, 90° angles between stem and tributaries, a construction sequence in which smaller optimized constructs are retained, constant-thickness branches, and so on [11,27,28], Figure 7a. Months later, we published the same problem [29] but we did it numerically by abandoning most of the simplifying assumptions (e.g. the construction sequence) used in the first papers, e.g. Figure 7b. In 1998 we revisited the problem numerically [18] in an area-point flow domain with random low-resistivity blocks embedded in a high-resistivity background by using the language of Darcy flow (permeability instead of conductivity and resistivity), Figure 6.

In summary, the three methods tried during the first 2 years of constructal theory taught us that trees with 'better performance', asymmetry, and 'more natural looks' are born as we progress in time, that is, as we endow the flow structure with more freedom to morph, Figures 8 and 9.

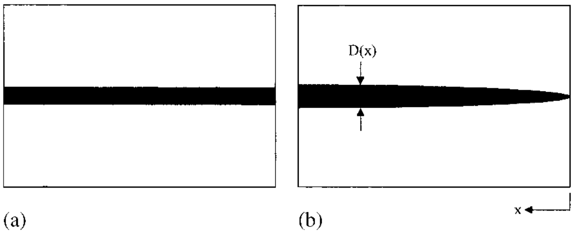

Figure 7. Elemental volume with high-conductivity channel (black) on a low-conductivity background: (a) uniform thickness and (b) optimal thickness for volume-to-point flow with minimal global resistance [29].

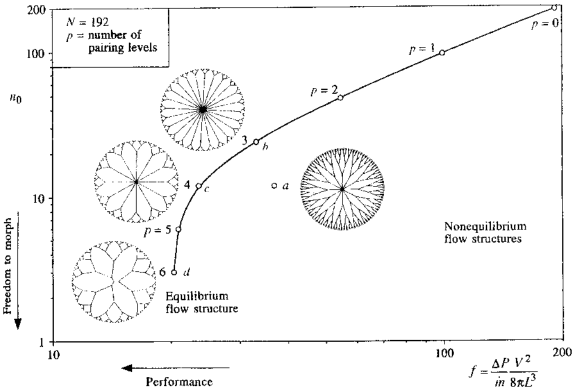

Figure 8. *Performance versus freedom* domain of laminar-duct flows that connect the center of a disc with 192 equidistant points on the perimeter [30].

Freedom is good for the performance and survival of a flow structure, be that natural or engineered, animate or inanimate, human or animal society, and so on. Design improvement without freedom to change the structure is nonsense. Rigid flow structures are brittle: dictatorial schemes and straight river channels are short lived.

The main idea that remains is the constructal law. Here is the 'click' that I felt as I ended my second paper on constructal trees ([11]; pp. 813–815; published on 1 November, 1996 because in 1996 the *International Journal of Heat and Mass Transfer* was experiencing an overflow of papers and was assigning 1997 numbers to issues that it was publishing in 1996):

> The commonality of these phenomena is much too obvious to be overlooked. It was noted in the past and most recently (empirically) in fractal geometry, where it was simulated based on repeated fracturing that had to be assumed and truncated. The origin of such algorithms was left to the explanation that the broken pieces (or building blocks, from the point of view of this paper) are the fruits of a process of self-optimization and self-organization. The present paper places a purely deterministic approach behind the word 'self': the search for the easiest path (least resistance) when global constraints (current, flow rate, size) are imposed.

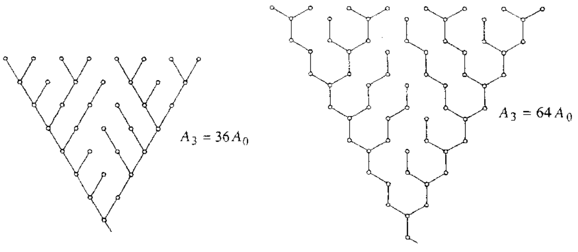

Figure 9. Emergence of asymmetry in the constructal layout of trees consisting of triangular and hexagonal area elements [31].

> If we limit the discussion to examples of living flow systems (lungs, circulatory systems nervous systems, trees, roots, leaves), it is quite acceptable to end with the conclusion that such phenomena are common because they are the end result of a long running process of 'natural selection'. A lot has been written about natural selection and the impact that efficiency has on survival. In fact, to refer to living systems as complex power plants has become routine. The tendency of living systems to become optimized in every building bloc and to develop optimal associations of such building blocks has not been explained: it has been abandoned to the notion that it is imprinted in the genetic code of the organism.
>
> If this is so, then what genetic code might be responsible for the development of equivalent structures in such nonliving systems as rivers and lightning? What genetic code is responsible for man-made networks (such as the trees in this paper)? Certainly not mine, because although highly educated, neither of my parents knew heat transfer (by the way, thermodynamics was not needed in this paper). Indeed, whose genetic code is responsible for the societal trees that connect us, for all the electronic circuits, telephone lines, air lines, assembly lines, alleys, streets highways and elevator shafts in multistory buildings?
>
> There is no difference between the living and the nonliving when it comes to the opportunity to find a more direct route subject to global constraints, for example, the opportunity of getting from here to there in an easier (faster) manner. If living systems can be viewed as

> engines in competition for better thermodynamic performance, then physical systems too can be viewed as living entities (animals!) in competition for survival. This analogy is purely empirical: we have an immense body of case-by-case observations indicating that flow configurations (living and nonliving) evolve and persist in time, while others do not. Now we know the particular feature (maximum flow access, minimum global flow) that sets each surviving design apart, but we have no theoretical basis on which to expect that the design that persists in time is the one that has this particular feature. This body of empirical evidence forms the basis for a new law of nature that can be summarized as (the constructal law, cited at the end of Section 2). This 'fourth law' brings life and time explicitly into thermodynamics and creates a bridge between physics and biology.

To the story of constructal trees I must add that I first worked on deducing trees for fluid flow (e.g. [28]); but when I saw how old, voluminous, and established the empirical (modeling) literature of this field is (from physiology to river morphology), I remembered hard lessons learned early in my career. It is risky for an amateur to submit something entirely new to an established group ['risk' means rejection and worse: loss of credit for the idea, because (in accordance with the constructal law) good ideas travel fast!]. The surer approach was to translate the idea into the safer language of minimum travel time [27] and minimal thermal-diffusion global resistance [11] in freely morphing area-point flows, and to submit the idea to peers who do not have an ax to grind. It worked, despite the 1-year delay that this double translation caused in the dissemination of the constructal law.

5. SCIENCE AS CONSTRUCTAL FLOW ARCHITECTURE

The evolution of thermodynamics from Carnot to EGM and now constructal theory is an illustration of a more general constructal phenomenon of evolution of flow configuration in time. Science, ideas, news, and education flow and cover the globe like the streams of river basins. They cover a multidimensional territory better known as history, geography, and civilization. The flow architecture of science continues to change, to improve, and to grow.

Physics is our knowledge of how nature works. Physics (or nature) is everything, including engineering: the biology and medicine of human+machine species. Our knowledge is condensed in simple statements (thoughts, connections), which evolve in time by being replaced by simpler statements. We 'know more' because of this evolution in time, not because brains become bigger and neurons smaller and more numerous. Our finite-size brains keep up with the steady inflow of new information through a process of simplification by replacement: in time, and stepwise, bulky catalogs of empirical information (e.g. measurements, data, complex empirical models) are replaced by much simpler summarizing statements (e.g. concepts, formulas, constitutive relations, principles, laws). A hierarchy of statements emerges along the way: it emerges naturally because it is better (cf. the constructal law).

The simplest and most universal are the laws. The bulky and the laborious are being replaced by the compact and the fast. In time, science optimizes and organizes itself in the same way that a river basin evolves: toward configurations (links, connections) that provide faster access or easier flowing. The bulky measurements of pressure drop *versus* flow rate through round pipes and saturated porous media were rendered unnecessary by the formulas of Poiseuille and Darcy. The measurements of how things fall (faster and faster and always from high to low) were rendered unnecessary by Galilei's principle and the second law of thermodynamics.

The hierarchy (specialization) that science exhibited at every stage in the history of its development is an expression of its never-ending struggle to optimize and redesign itself. Hierarchy means that measurements, *ad hoc* assumptions, and empirical models come in huge numbers, a 'continuum' above which the compact statements (the laws) rise as needle-shaped peaks. Both are needed, the numerous and the singular. One class of flows (information links) sustains the other. The many and unrelated heat engine builders of Britain fed the imagination of one Sadi Carnot. In turn, Sadi Carnot's mental viewing (thermodynamics today) feeds the minds of contemporary and future builders of all sorts of machines throughout the world.

Civilization with all its constructs (science, religion, language, writing, etc.) is this never-ending physics of generation of new configurations, from the flow of mass, energy, and knowledge to the world migration of the special persons to whom ideas occur (the creative). Good ideas travel. Better flowing configurations replace existing configurations (the constructal law). Empirical facts (observations) are extremely numerous, like the hill slopes of a river basin. The laws are the extremely few big rivers, the Seine and the Danube.

6. THERMODYNAMICS OF FLOW SYSTEMS WITH CONFIGURATION

Thermodynamics has reached an impasse similar to the development of the heat engine two centuries ago [7,32]. The need is great, the value of research and education is obvious, and valuable improvements are occurring every day. What is missing is a scientific base, a fundamental framework that ties together what is being achieved and guides us into the future. We all know the headlines: chaos *versus* order, Darwinism *versus* design in nature, globalization, diminishing energy resources, environmental impact, and sustainable development.

An impasse is a historic opportunity for science. It is the moment to spring into a new direction and to march loudly against the crowd. Fuels are not given, environments are not infinite, and energy transformations do not occur in isolation. Flow systems are not black boxes with inflows and outflows and no structure internally. The real world (nature, physics) has structure, organization and pattern. Until now, thermodynamics was not concerned with the architecture (the drawings) of the systems that inhabit its black boxes.

The route to historic impact is paved with fundamentals. In the thermodynamics that emerges, the readjustments of fossil and renewable fuel streams (i.e. new equilibria of *how* to flow) are being predicted and optimized based on principles. In this new science, the shrinking of the environment (i.e. new equilibria between our flows and the external ones) is predicted and optimized based on principles. Thermodynamic systems have new properties such as configuration, objective, svelteness, and freedom to morph. The new science is by its very nature transdisciplinary—a science of systems of systems.

No flow system is an island. No river exists without its wet plain. No city thrives without its farmland and open spaces. Everything that flowed and lived to this day to 'survive' is in an optimal balance with the flows that surround it and sustain it. The air flow to the alveolus is optimally matched to the blood that permeates through the vascularized tissue and *vice versa*.

Yes, *vascularized* is a good way to describe the systems that the new science of thermodynamics will cover. The tissues of energy flows, like the fabric of society and all the tissues of biology, are optimized architectures. Not just 'any' architectures, as in the black boxes of classical thermodynamics, but the equilibrium, or the near-equilibrium flow architectures. The climbing to this high podium of performance is the transdisciplinary effort—the balance between seemingly unrelated flows, territories, and disciplines. This balancing act—the optimal distribution of imperfection—generates the very design of the process, power plant, city, geography, and economics.

The need for considering the whole—the macroscopic system—is great and universal. No matter how successful we are in discovering and understanding small-scale phenomena and processes, we are forced to face the challenge to assemble the invisible elements into palpable devices. The invisible grains must be kept alive with flows, which connect them, and serve them. The challenge is to construct, that is, to connect, and optimize while assembling.

This challenge is becoming increasingly difficult. While the smallest scales are becoming smaller, the number of components and the complexity of the useful device (always macroscopic) become greater. A good example is the rush to *nanotechnology*. Technology means more than the new physical phenomena that may appear on the frontiers of progressively smaller scales. A technology is truly new when it is made useful in the form of macroscopic devices that improve our lives. Usefulness means that we must discover principles of constructing, connecting, and packing multiscale flow systems into macroscopic spaces.

The new gadgets are like the engines in the invasion contemplated by Carnot (Section 2). Certain is that they will all be forgotten, *unless* there is a Sadi Carnot watching, to see a pattern and immortalize it with a short page in the thin book of principles. This happens only rarely and when it does it illustrates again the constructal principle of ‘one sustains the crowd’ (Section 5).

And so, I arrive at the essence of constructal theory or the thermodynamics of nonequilibrium systems with configuration—the union that it forges between physics, engineering science, and life sciences. We see this union in Figure 10. Earth, with its solar heat input, heat rejection, and wheels of atmospheric and oceanic circulation, is a heat engine without shaft: its maximized (but not ideal) mechanical power output cannot be delivered to an extraterrestrial system. Instead, the earth engine is destined to dissipate through air and water friction and other irreversibilities (e.g. heat leaks) all the mechanical power that it produces. It does so by ‘spinning in its brake’ the fastest that it can (hence the winds and the ocean currents, which proceed along easiest routes). Because the flowing earth is a constructal heat engine, its flow configuration has evolved in such a way that it is the least imperfect that it can be. It produces maximum power, which it then dissipates at maximum rate. A principle of maximum dissipation is now being invoked *ad hoc* in geophysics: all such writings refer only to what goes on in the brake and are already covered by the constructal law.

The heat engines of engineering and biology (power plants, animal motors) have shafts, rods, legs, and wings that deliver the mechanical power to external entities that use the power (e.g. vehicles and animal bodies needing propulsion). Because the engines of engineering and biology are constructal, they morph in time toward flow

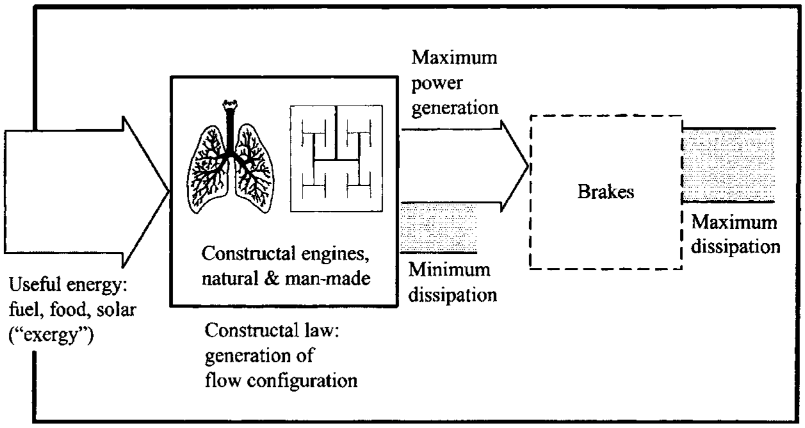

Figure 10. Every nonequilibrium (flow) component of the earth functions as an engine that drives a brake [33]. The constructal law governs ‘how’ the system functions: by generating a flow architecture that distributes imperfections through the flow space and endows it with configuration. The ‘engine’ part evolves in time toward generating maximum power (or minimum dissipation), and as a consequence, the ‘brake’ part exhibits maximum dissipation. Evolution means that each flow system assures its persistence in time by freely morphing into easier and easier flow structures under finiteness constraints. The arrows proceed from left to right because this is the general drawing for a flow (nonequilibrium) system, in steady or unsteady state. When equilibrium is reached, all the flows cease, and the arrows disappear.

configurations that make them the least imperfect that they can be. Therefore, they evolve toward producing maximum mechanical power (under finiteness constraints), which, for them, means a time evolution toward minimum dissipation (minimum entropy generation rate).

If we look outside an engineering or biology engine, we see that all the mechanical power that the engine delivers is destroyed through friction and other irreversibility mechanisms (e.g. transportation and manufacturing for man, animal locomotion, and body heat loss to ambient). The engine and its immediate environment (the brake), as one thermodynamic system, are analogous to the whole earth (Figure 10). After everything is said and done, the flowing earth (with all its engine+brake components, rivers, fish, turbulent eddies, etc.) accomplishes as much as any other flow architecture, animate, or inanimate: it mixes the earth's crust most effectively—more effectively than in the absence of constructal phenomena of generation of flow configuration.

Irrefutable evidence of this accomplishment is how all the large eddies of biological matter have morphed and spread over larger areas and altitudes, in this sequence in time: fish in water, walking fish and other animals on land, flying animals in the atmosphere, flying man+machine species, and man+machine species in the outer space. The balanced and intertwined flows that generate our engineering, economics, and social organization are no different than the natural flow architectures of biology (animal design) and geophysics (river basins, global circulation).

NOMENCLATURE

Symbols

A_0 = elemental area (m^2)
A_3 = third construct (m^2)
D = blade thickness (m)
e_x = specific flow exergy ($\mathrm{J\,kg^{-1}}$)
$\dot{E}$ = exergy rate (W)
f = dimensionless flow resistance
L = disc radius (m)
$\dot{m}$ = mass flow rate ($\mathrm{kg\,s^{-1}}$)
n_0 = number of ducts that reach the disc center
p = number of pairing levels
$\dot{S}_{gen}$ = entropy generation rate ($\mathrm{W\,K^{-1}}$)
$\dot{S}''_{gen}$ = volumetric entropy generation rate ($\mathrm{W\,m^{-3}\,K^{-1}}$)
T_0 = environment temperature (K)
V = total flow volume (m^3)
$V_{x,\infty}, V_{y,\infty}$ = velocity components ($\mathrm{m\,s^{-1}}$)
$\dot{W}$ = power output (W)
$\dot{W}_{rev}$ = power output in the reversible limit ($\mathrm{W\,K^{-1}}$)
x, y = cartesian components
η_{II} = second-law efficiency of power plants, Figure 1
ΔP = pressure difference (Pa)
ν = kinematic viscosity ($\mathrm{m^2\,s^{-1}}$)

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