

## EVOLUTION AS PHYSICS

ADRIAN BEJAN

*Abstract.* Thermodynamics today is the physics domain in which three previously self-standing lines of thinking merged to cover the broadest range of natural phenomena to date. The three lines were work-heat-design, or mechanics-caloric-evolution. Covered now as ‘physics’ are the previously separate domains of biology, technology, economics, and social organization. The purpose of this brief article is to outline this broad coverage by drawing attention to the new terms, physical properties, and concepts that have crept into physics, for example: freedom, evolution, performance, objective, purpose, better, design, configuration, optimization, complexity, diversity, hierarchy, size, wealth, equality, and economies of scale. Along the way, I clarify some of the most common misconceptions that persist in this expanded domain of physics. In sum, this is a brief look at the evolution of thermodynamics and how the traditional concept of ‘evolution’ itself fits in this new scientific framework.

*Key words:* constructal, evolution, hierarchy, wealth, life, death, physics, economics.

### 1. EVOLUTION

Evolution means changes that happen in a discernible direction over time [1, 2]. We are the ones who observe, discern, invent science and put its powers to use. The concept of ‘evolution’, like all science, is a human construct, and it is in play widely because it is useful.

Thermodynamics illustrates the evolution phenomenon in two ways (Fig. 1). First, as its name indicates, thermodynamics is the science of converting heating into work (power), and power into heating. In applied physics and engineering, thermodynamics is the science of ‘power’: processes and devices that generate and use power, their functioning, design, performance and opportunities for improvement. Second, the body of science that thermodynamics represents has been evolving to become simpler, clearer, more general and more useful. Heating and working are the two streams of knowledge that empowered humans and merged into “thermo-dynamics” in the mid-1850s. The merger was summarized as the first and the second law. With the constructal law\* of 1996 [3–7] thermodynamics now covers the universal phenomenon of design occurrence and evolution.

---

Duke University, Department of Mechanical Engineering and Materials Science, Durham, NC 27708-0300, USA

\* “For a finite-size flow system to persist in time (to live) it must evolve freely such that it provides greater access to its currents.”

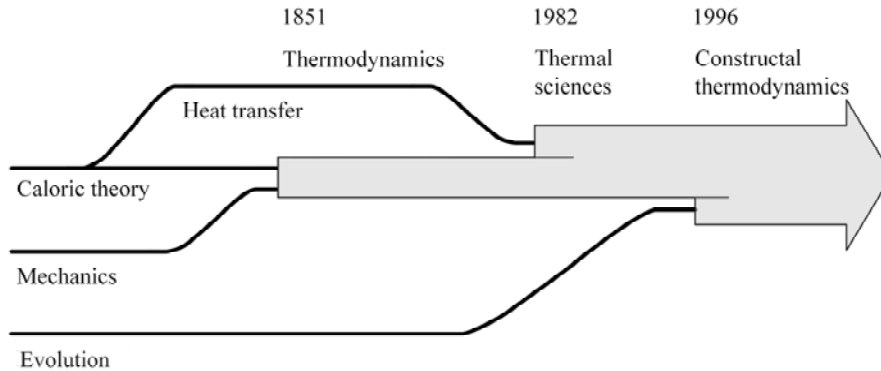


Fig. 1 – The evolution and spreading of thermodynamics during the past two centuries.

As a discipline, thermodynamics emerged from the human need to have power, to enhance the effect of human effort. It is a natural urge to want power, to move things, including what flows through the live human body. All our urges – to have life, food, shelter, knowledge, space, and continuity – are design features that facilitate the movement of all animal mass over the Earth. Without such designs our mass would not be moving as easily and as far. Without other flow designs (exergy streams, better known as power, food and fuel), our mass would not be moving at all.

In the entire physical world, all systems (natural and man-made) follow the law of physics of evolution, the constructal law: they evolve their designs over time in the direction of easier movement. The net result of civilization's advance in knowledge and technology is that we move more mass over greater distances on earth. The laws of physics lead us fast and straight, not on a blind and crooked path of trial and error.

All science is an evolving design – a human contrivance, an add-on – that empowers the thinkers who possess it. The history of thermodynamics is a wonderful example of how science evolves (Fig. 1). In the beginning, there were two branches of science, mechanics and caloric theory, which were complementary, successful and useful. These two merged into a doctrine that was simpler, more general, and more powerful. More recently, thermodynamics spread over the broad domain of evolutionary design, which covers everything, just like the manifestations of the natural tendencies summarized as the first law and the second law.

All scientists, physicists and engineers, share a common respect and charge for understanding and using what we know of the natural world. Broadly speaking, engineers tend to be more applied, and physicists tend to be more theoretical, but this is not a demarcation line. If there is a line, it is blurry, easily crossed, with some of us who jump over the line in both directions, over and over. More simply, we are all scientists, some more at home in theory, others more at home in applications, and a few Lone Rangers who roam freely on the earth of ideas.

Creativity – the gift to have original ideas (images) occurring in the mind – is what unites us as scientists. Science is an evolving story, and the better story is the better science. Science with engineering is a much better story than science without engineering.

The first law and the second law are more than 150 years old. They had enormous influence on the science and the vocabulary that emerged since the 1800's. Yet, during all this time most of the applications in which the two laws were relied upon had 'objective'. They were about improving performance, efficiency, fitness, survivability (robustness, resilience), and so on. The existence of objective was taken as evident in all the domains of application, from machines (i.e., from the original domain of thermodynamics) to animal 'design', transportation, river basin architecture, urban design, technology and economics.

From the beginning, the science of heat engines was about changing and improving a design, which means changing the existing flow configuration of the thermodynamic system. Carnot himself was most interested in efficiency, and devoted his memoir to lessons for how to make changes that lead to increases in efficiency in the future (examples: avoid friction and heat transfer across a finite temperature difference). New work during the same 150 years was stimulated by the 'objective' tendency and all its related manifestations, from efficiency to survivability. Today, the code name for this urge is sustainability. Thermodynamics was enriched with new methods for performing analyses that lead to improved performance. The concepts of irreversibility, entropy generation and of 'useful work' emerged very early in the evolution of thermodynamics. The associated concept of *destroyed* useful work has become the thermodynamic currency for evaluating the opportunity for improving the performance of any system (closed, open) that executes any process (steady, unsteady, cycle). Through changes in the flow architecture of the system, the doctrine teaches how to reduce the destruction of useful work, or exergy, which is the same as reducing the generation of entropy. This has become known as the entropy generation minimization method and exergy analysis and the minimization of exergy losses.

During the second half of the 20<sup>th</sup> century, the 'design' line in thermodynamics was dominated by concerns with 'costs'. One cannot overlook economics when pursuing better designs, which produce a more useful effect per unit of expensive input. Even in animal design, which is theorized as an evolutionary flow architecture with direction over time, the common-sense concept of 'cost' is accepted. In engineering in particular, where the physical components of the system must be manufactured from purchased materials, the preoccupation with cost has generated an entire literature dedicated to the thermodynamic cost of materials, organs, and designs. This point of view has become known as 'embodied exergy', and serves as analytical structure for thermoeconomics [8].

Design requires synthesis, a holistic view: selecting and putting together components to form a smoothly working whole. To optimize means to opt, to

make choices [9]. It does not mean to take the derivative of a continuous function and set it equal to zero. Design also requires visualization, still images and evolutionary images of macroscopic systems, flowing and morphing. Design thinking is oriented contrary to reductionism. It is holistic, against the infinitesimal. Shape, structure, flow architecture and their joint evolutionary future are the object of design.

The physics meaning of life & evolution is evident and unambiguous. The basis of such clarity is provided by thermodynamics and geometry. Here is how, in three simple steps [1]:

(1) The *dead state* is the physical being of a system when nothing flows (nothing moves) inside the system, or between the system and the environment (which is the other system, the rest). In the dead state, nothing changes, not the configuration, and not the system properties. This happens when the system is in complete (unrestricted) equilibrium with its environment. The dead state is the still image of the dead system.

(2) The *live state* is the opposite of the dead state. Live is the state of a system with two physical features present at the same time: flow (movement, inside and across its boundary with the environment), and morphing configuration (shape, structure, form, drawing, boundaries, i.e. design) that changes freely while the system flows. The live state is recognized by additional names in the literature: active matter, functional materials, self-healing, self-cooling, animal design, etc.

(3) *Evolution* is the sequence of flow configurations that the live system exhibits over time. This is where geometry meets thermodynamics. Two figures are different when, if superimposed, the lines of the first do not match faithfully the lines of the second. Today's flow configuration must be different than yesterday's. The future must be different than the past. Evolution means change in geometry, which occur one way, in a goal-oriented direction in time (see the next section). Think of evolution as "geometric irreversibility", which means that the geometric figure (the flow architecture) evolves in such a way that it does not return to its original form and size. The geometric figure evolves *one way*, to provide greater access to what flows in it.

## 2. RECENT WORK

In this section, I draw attention to my most recent publications on evolution as physics, the phenomenon summarized as the constructal law. The broadest coverage of this phenomenon and principle is in my books for the general public [1, 7].

### (a) Economies of scale

Why is size so important? Why are "economies of scale" a universal feature of all flow systems, animate, inanimate and human made? The empirical evidence is clear: the bigger are more efficient carriers (per unit) than the smaller (Fig. 2)

[10]. This natural tendency is observed across the board, from animal design to technology, logistics and economics. In Ref. [11] we relied on physics (thermodynamics) to determine the relation between efficiency and size. The objective is to predict a natural phenomenon, which is universal. It is not to model a particular type of device. The objective is to demonstrate based on physics that the efficiencies of diverse power plants should increase with size. The analysis is performed in two ways. First is the tradeoff between the ‘external’ irreversibilities due to the temperature differences that exist above and below the temperature range occupied by the circuit executed by the working fluid. Second is the allocation of the fluid flow irreversibility between the hot and cold portions of the fluid flow circuit. The implications of this report in economics and design science (scaling up, scaling down) and the necessity of multi-scale design with hierarchy are discussed.

(b) Wealth inequality

‘Inequality’ is a common observation about us, as members of society (Fig. 3). In Ref. [12] we unify physics with economics by showing that the distribution of wealth is closely related to the evolutionary movement of all the streams of a live society. The hierarchical distribution of movement on the surface of the earth happens naturally. We illustrate this with two architectures, river basins and the movement of freight. The physical flow architecture that emerges is hierarchical on the surface of the earth and in everything that flows inside the live human bodies, the movement of humans and their belongings, and the engines that drive the movement. The nonuniform distribution of movement (wealth) becomes more accentuated as the economy becomes more developed, i.e., as its flow architecture becomes more complex for the purpose of covering smaller and smaller interstices of the overall (fixed) territory. It takes a relatively modest complexity for the nonuniformity in the distribution of movement (wealth) to be evident. This theory also predicts the Lorenz-type distribution of income inequality, which was adopted empirically for a century.

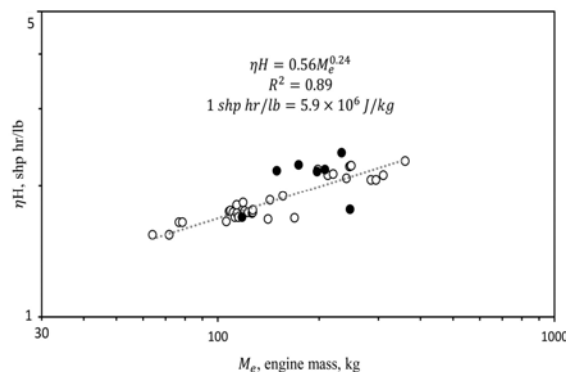


Fig. 2 – The correlation between helicopter engine efficiency and engine size. In the indicated correlation, the military helicopter data (the black circles) were not included [10].

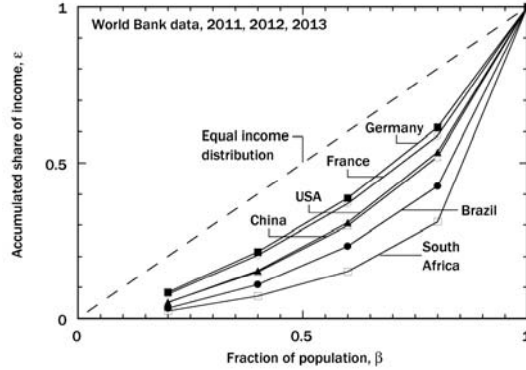


Fig. 3 – The accumulated share of income  $\varepsilon$  held by the fraction of the population ( $\beta$ ) [12].  
Data adapted from the World Bank Development Indicators, World Bank, 2016.

### (c) Hierarchy

In Ref. [13] we show that bodies of the same size, suspended uniformly in space constitute a system (a “suspension”) in a state of uniform volumetric tension because of mass-to-mass forces of attraction. The system evolves faster to a state of reduced tension when the bodies coalesce nonuniformly, i.e., hierarchically, into few large and many small bodies suspended in the same space (Fig. 4). Hierarchy, not uniformity, is the evolutionary flow design that emerges over time. The implications of this finding in the physics of natural organization are discussed.

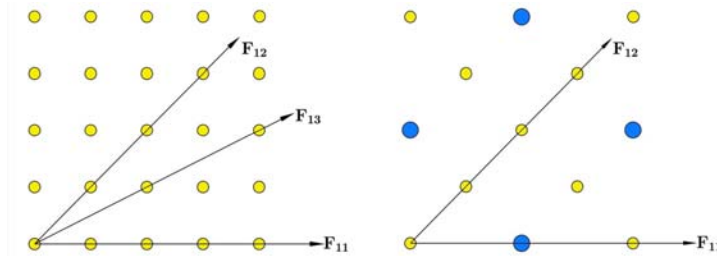


Fig. 4 – Hierarchy: few large and many small in the accretion of equidistant masses [13].

### (d) Technology evolution

In Ref. [10] we show that during their half-century history, helicopters have been evolving into geometrically similar architectures with surprisingly sharp correlations between dimensions, performance and body size. For example, proportionalities emerge between body size, engine size and the fuel load. Furthermore, the engine efficiency increases with the engine size, and the propeller radius is roughly the same as the length scale of the whole body. These trends are in accord with the constructal law, which accounts for the engine efficiency trend

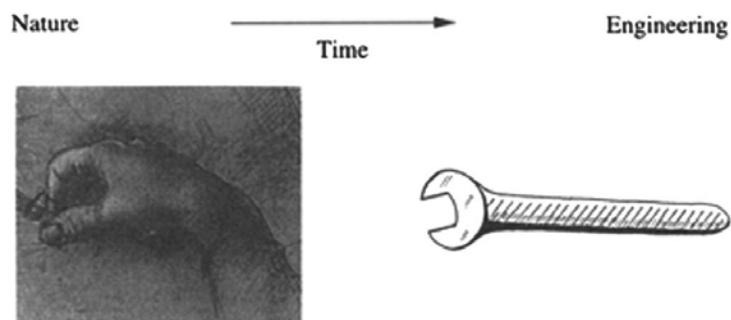
and the proportionality between ‘motor’ size and body size in animals and vehicles. These body-size effects are qualitatively the same as those uncovered earlier for the evolution of airplanes [14]. The present study adds to this theoretical body of research the evolutionary design of helicopters during their modern development.

(e) Water and energy

People like to say that energy and water are two problems, two vital commodities in short supply. In Ref. [15] I draw attention to the emerging literature and physics principle that provide the scientific foundation for “sustainability”. I show that the sustainability need is about *flow*: the flow of energy and the flow of water through the inhabited space. All the flows needed for human life (transportation, heating, cooling, water) are driven by the purposeful consumption of fuels. This is why the wealth of a country (the GDP) is directly proportional to the annual consumption of fuel in that country. This organization happens, it is natural. Sustainability is the one-word need that covers all the specific needs. Sustainability comes from greater freedom in changing the organization—the flow architecture—that sustains life. Greater freedom to change the design (from water and power to laws and government) leads to greater flow, wealth, life and longevity, i.e. sustainability.

(f) Human & machine species

Humans and technology are not in symbiosis. They are one species, not two. Humans, enveloped in artifacts of many kinds and ages (from writing, to airplanes, Fig. 5), are evolving as one species, the “human & machine species”. This evolution is visible and recorded in our lifetime. In Ref. [16] I illustrate the evolution of the human & machine species by focusing on commercial aircraft, the cooling of electronics and modern athletics, which is a special laboratory for witnessing the evolution of animal locomotion. These evolutionary forms of flow organization are in accord with, and can be predicted based on the law of physics that governs evolution in nature, bio and non-bio: the constructal law. Evolution, life and the human & machine species are physics.



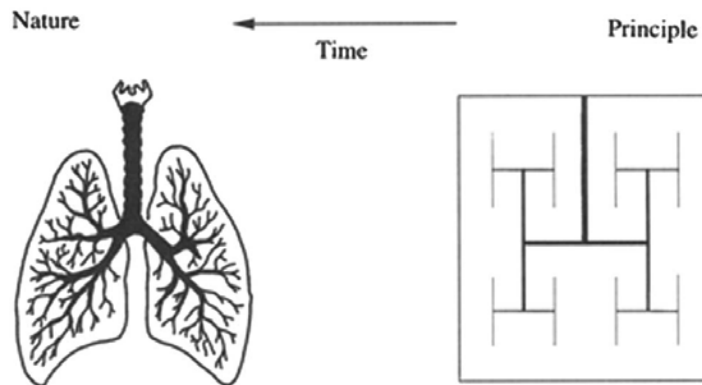


Fig. 5 –The contrivance (machine) is an attachment (an artefact) that enhances the impact of human action on the environment. The occurrence and proliferation of artefacts is a constructal-law tendency. This drawing from 2000 [6] shows the fundamental difference between empiricism (top) and theory (bottom).

### 3. THE TEN MOST COMMON MISUNDERSTANDINGS

Thermodynamics is brief, simple, unambiguous and improving. Yet, confusion reigns in public discourse and scientific papers. The words “thermodynamics” and “entropy” are pasted on new concepts without respect for their proper meaning. In Ref. [17], I made an attempt to clarify this situation. Here are the most common misunderstandings:

(i) What thermodynamics is

As its name indicates, ‘thermo-dynamics’ is the modern science of heat and work and their usefulness, which comes from converting the work (power) into movement (life) in flow architectures that evolve over time to facilitate movement (Fig. 1). The part of nature that thermodynamics represents is this: nothing moves by itself unless it is driven by power, which is then destroyed (dissipated) during movement. Nothing evolves unless it flows and has the freedom to change its architecture such that it provides greater and easier access to the available space.

Thermodynamics grew out of engineering from the human urge to have power, to enhance the effect of human effort. From the beginning, this science was about improving a design, which means changing the existing flow configuration of the thermodynamic system. With thermodynamics, humanity made enormous leaps while guided by the ‘objective’ urge and all its related manifestations and concepts, from cheap power, efficiency and economic sense to sustainability.

(ii) Nature is complicated

Not if you see nature from thermodynamics! Nature is the simplest thought imaginable, because she (natura) consists of only two systems, your system (the portion selected by you, the observer, for contemplation) and the rest, which is also



selected by you (the environment). Process means the change in the state of the thermodynamic system. State is the collection of numerical values that represent the system features, which are called properties.

If your chosen system generates power in order to move through its environment, then the world that you contemplate behaves as an engine & brake whole. Through movement, the brakes dissipate the power generated by the engines. Others may contemplate other systems that generate power and movement (waterfalls, animals, atmospheric and oceanic currents). For all the thinkers together, the same world as yours is an endless collection of intertwined (embedded) engine & brake flow systems.

(iii) What the second law is

Like any other law of physics, the second law of thermodynamics is a concise statement of a universal tendency (a phenomenon) in nature. The tendency of the second law is irreversibility, the fact that everything by itself flows one way, from high to low. Here is the correct statement of the second law, made by two of the three original proponents (the first was Rankine):

Clausius: No process is possible whose sole result is the transfer of heat from a body of lower temperature to a body of higher temperature.

Kelvin: Spontaneously, heat cannot flow from cold regions to hot regions without external work being performed on the system.

A new law does not have to be stated in mathematical terms. The second law and the constructal law were stated in words, each as a mental viewing, not in mathematical code. The mathematical second law came after the invention of the derived property called 'entropy', and the analytical constructal framework emerged along the way [18].

(iv) What is entropy and how can it be measured?

What can be measured is the change in the entropy inventory of a special closed system selected for this measurement. Entropy change from state 1 to state 2 is the name for the integral of  $\delta Q/T$  during a specially selected 'reversible' process from state 1 to state 2, where  $\delta Q$  is the infinitesimal flow of heat from the environment to the system during the process, and  $T$  is the contact temperature (kelvin) of the system, at the spot crossed by  $\delta Q$ . A reversible heating process is so special (and not real) that at any time between state 1 and state 2 the system is isothermal and in equilibrium with its environment, which is the heat source.

(v) Principle of entropy increase

There is no such principle, and whether the entropy (or some other property) of your system increases depends on how you select your system. This misconception is due to the (correct) notion that for a closed system that cannot experience heat transfer with its environment (called adiabatic, a very special closed system) that the second law states that the system entropy inventory (a property) increases in time, while 'any' unspecified change occurs inside the

system. An even more special closed system is an isolated system (closed, no heat transfer, no work transfer).

Because of the second law statement for such special cases, many believe that the second law accounts for organization, evolution, life, death, and the arrow of time. This is false. The second law says nothing about architecture, evolution (design change) and the arrow of time. It is the law of physics of the natural phenomenon of irreversibility.

The second law and ‘entropy’ have nothing to say about form and time arrow. The belief that the arrow of time in nature is imprinted on one-way (irreversible) phenomena is mistaken. Only in an imagined ‘isolated system’ the claimed arrow of time points somewhere, namely, toward “nothing moves”, which means the dead state, not the live (evolving) nature all around us. The correct arrow of time is painted visibly on live phenomena: the evolution of flow organization throughout nature, animate and inanimate, which is represented by the constructal law [1, 19].

(vi) Maximum and minimum (sic) entropy generation

We often hear that the organization that we see all around is governed by a maximum or minimum principle. This contradicts logic, not just thermodynamics. Minimizing entropy generation cannot be the same as maximizing entropy generation, and minimizing resistance cannot be the same as maximizing resistance. Because of the word “entropy” spoken in such claims, many believe that minimization and maximization are covered by the second law, which is false.

(vii) Disorder is increasing

Observed is also the opposite, which is the ubiquitous phenomenon of design evolution in nature. Order is in the eye of the observer. Where many see the trivial (diversity), few see the subtle (order, organization, principle). The second law says nothing about “disorder”: review Clausius’ and Kelvin’s statements.

Many confuse the second law with the view that in a box filled with particles the assembly tends toward a larger number of probable states, from which the claim that the second law is probabilistic. This is the core idea of statistical mechanics, which is a self-standing younger field, not thermodynamics.

To assume a swarm of particles in a closed box is to throw away the “any system” power of thermodynamics. The any-system is the most general system, while the box with bouncing particles is the extremely special, the local, the extremely particular system with a configuration chosen.

Even in an isolated system that proceeds toward death according to the second law, the natural emergence of organization and evolution is plain to see. Think of an isolated system initially filled nonuniformly with fluid (high pressure on one side of a partition, and low pressure on the other side), and you will recognize the birth of macroscopic organization, flow structure and evolution (turbulence, jets, eddies). Think of an isolated system containing initially two bodies in a vacuum, one with positive charges and the other with negative charges. En route to its second-law death, the isolated system impresses us with lightning, which is macroscopic flow

organization and evolution. This, the evolution is accounted for by the constructal law, not by the second law. Of course, the system obeys all the laws.

(viii) The laws of thermodynamics hold only for closed systems

The laws of thermodynamics are universally valid, for any system, closed or open. The confusion stems from the birth of thermodynamics at the confluence of the ‘heat’ and ‘work’ lines (Fig. 1), when the system that preoccupied the pioneers was a closed system: a heat engine operating in cycles or in steady state, while in communication with two temperature reservoirs, the fire and the ambient. The laws were generalized to apply to open systems during the second half of the 1800s. None of the advances made in the technologies that generate and use power today would have been possible without the correct application of the laws of thermodynamics to systems that are modeled as open and time dependent, which is the most general model, the “any system” object of thermodynamics.

(ix) The laws of thermodynamics pertain to equilibrium states

This is contradicted by the presence of the inequality sign in any mathematical restatement of the second law, which refers to the universal tendency of irreversibility in all the flows, inside the system and between system and environment. Flows happen because of temperature and pressure differences. Systems with differences are not in equilibrium. In fact, most of the systems modeled after nature and defined in engineering and physics are in nonequilibrium states.

(x) Analogy between heat and work

The claimed analogy (called ‘entransy’) between heating a solid body (heat transfer) and charging an electrical capacitor (work transfer) violates the second law [2, 17]. Charging a capacitor is analogous to stretching a spring, not to heating a body. Both processes are driven by work transfer. Work must be done to stretch the spring and to move charge between the plates of the capacitor. The elongation of the spring, and the separation between plates (voltage, spacing) are macroscopic features.

Heat and work are eminently different. This is why thermodynamics emerged as a new science (Fig. 1). Had work and heat been analogous, the heat line would have been absorbed into the older line, mechanics, not thermodynamics. The heat-work analogy is a mistake of the same order as a claimed invention of a perpetual motion machine [2, 17].

#### 4. WHAT IS TO BE DONE

Defend and improve science. Teach thermodynamics and the meaning of its concepts correctly. Why, because they are good, useful and true.

Science evolves, as an add-on to the evolving human & machine species. What works is kept, as an add-on to the architecture that was flowing before. What

is false is swept aside, and forgotten. This is the evolutionary ‘morphing’ design that science is.

Science is self-correcting. This key truth of science needs to be broadly communicated to all, not just scientists.

*Received on March 10, 2017*

#### REFERENCES

1. BEJAN, A., *The Physics of Life: The Evolution of Everything*, St. Martin’s Press, New York, 2016.
2. BEJAN, A., *Advanced Engineering Thermodynamics*, 4<sup>th</sup> ed., Wiley, Hoboken, 2016.
3. BEJAN, A., *Street network theory of organization in nature*, J. Adv. Transportation, **30**, 2, pp. 85–107, 1966.
4. BEJAN, A., *Constructal-theory network of conductive paths for cooling a heat generating volume*, Int. J. Heat Mass Transfer, **40**, 4, pp. 799–816, 1997.
5. BEJAN, A., *Advanced Engineering Thermodynamics*, 2<sup>nd</sup> ed., Wiley, New York, 1997.
6. BEJAN, A., *Shape and Structure, from Engineering to Nature*, Cambridge University Press, New York, 2000.
7. BEJAN, A., ZANE, J.P., *Design in Nature: How the Constructal Law Governs Evolution in Biology, Physics, Technology and Social Organization*, Doubleday, New York, 2012.
8. BEJAN, A., TSATSARONIS, G., MORAN, M., *Thermal Design & Optimization*, Wiley, New York, 1996.
9. BEJAN, A., *Constructal law: optimization as design evolution*, J. Heat Transfer, **137**, p. 061003, 2015.
10. CHEN, R., WEN, C.Y., LORENTE, S., BEJAN, A., *The evolution of helicopters*, J. Appl. Phys., **120**, p. 014901, 2016.
11. BEJAN, A., ALMERBATI, A., LORENTE, S., *Economies of scale: the physics basis*, J. Appl. Phys., **121**, p. 044907, 2017.
12. BEJAN, A., ERRERA, M.R., *Wealth inequality: the physics basis*, J. Appl. Phys., **121**, p. 124903, 2017.
13. BEJAN, A., WAGSTAFF, R.W., *The physics origin of the hierarchy of bodies in space*, J. Appl. Phys., **119**, p. 094901, 2016.
14. BEJAN, A., CHARLES, J.D., LORENTE, S., *The evolution of airplanes*, J. Appl. Phys., **116**, p. 044901, 2014.
15. BEJAN, A., *Sustainability: the water and energy problem, and the natural design solution*, European Review, **23**, pp. 481–488, 2015.
16. BEJAN, A., *Evolution as physics: the human & machine species*, European Review, **25**, pp. 140–149, 2016.
17. BEJAN, A., *Evolution in thermodynamics*, Applied Physics Reviews, **4**, p. 011305, 2017.
18. BEJAN, A., LORENTE, S., *The constructal law and the evolution of flow systems with configuration*, Int. J. Heat Mass Transfer, **47**, pp. 3203–3214, 2004.
19. BEJAN, A., *Maxwell’s demons everywhere: evolving design as the arrow of time*, Scientific Reports, **4**, p. 4017, 2014.