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Evolution in thermodynamics

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This review covers two aspects of "evolution" in thermodynamics. First, with the constructal law, thermodynamics is becoming the domain of physics that accounts for the phenomenon of evolution in nature, in general. Second, thermodynamics (and science generally) is the evolving add-on that empowers humans to predict the future and move more easily on earth, farther and longer in time. 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 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. I also review the rich history of the science, and I clarify misconceptions regarding the second law, entropy, disorder, and the arrow of time, and the supposed analogy between heat and work. *Published by AIP Publishing.*
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I. OBJECTIVE: TWO ASPECTS OF EVOLUTION

Evolution means changes that happen in a discernible direction over time.[1] 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 "thermodynamics" in the mid-1850s. They represent a wonderful story of scientific discovery and goodness. The universal phenomenon of evolution has become an integral part of thermodynamics.

The focus is on the physics, on what "happens" all around us and inside of us, and on the emerging science that empowers us. Science is the search to uncover the truth about nature with humans in it, which is why scientists constantly review and reword the discovery so that it serves humanity better in the generations that follow.

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. These human urges are

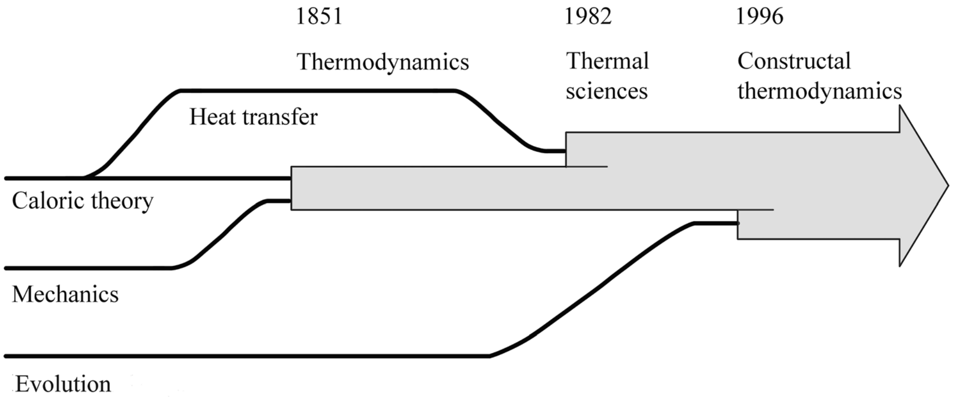


FIG. 1. The evolution and spreading of thermodynamics during the past two centuries.

better known by older names. For example, the urge to have life is the survival instinct. The urge to have continuity is the instinct to generate offspring, and protect the offspring with resources during life time and beyond, which is why wealth, peace, and "sustainability" are considered good, without questioning.[1]

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 physical world, all systems natural and man-made follow a law of physics of evolution: 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.

In this review I present a bird's-eye-view of thermodynamics from its heat-engine origins in the 1700s to the present day. This review is strictly about the science of "power," which is the mother river of a very wide domain that keeps expanding. The laws of thermodynamics reviewed here cover *any* system, regardless of its (unspecified) configuration. There are several more recent fields that have been given names that include the word "thermodynamics" (statistical, information, cognition, etc.): such fields are different, self-standing, and are not the subject of this review.

II. THE "HEAT" AND "WORK" LINES

All science is an evolving design—a human contrivance, an add-on—that empowers the thinkers who possess it (see also Section VIII). 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. That doctrine is thermodynamics, born in 1851–1852 out of the writings of Rankine, Clausius, and William Thomson (Lord Kelvin). 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.

Table I shows some of the highlights of discovery along the disconnected routes of mechanics and caloric theory. These highlights come from many sources: Rumford,[3] Carnot,[4] Mayer,[5] Joule,[6,7] Rankine,[8] Clausius,[9] Tait,[10] Gibbs,[11] Poincaré,[12] Newton,[13] Bernoulli,[14] Helmholtz,[15] Gillispie,[16] Born,[17] Brown,[18] Andrade,[19] Laue,[20] Mendoza,[21] Cardwell,[22] Planck,[23] Kestin,[24] Truesdell,[25] Romer,[26] Lemons and Penner,[27] and Kakac.[28] Four brief portraits are indicative of this exciting period:

- Nicolas Leonard Sadi Carnot (1796–1832) graduated as a military engineer from the École Polytechnique, Paris, and in 1824 published the book *Reflexions on the Motive Power of Fire*, which kick-started thermodynamics.
- Jean Baptiste Joseph Fourier (1768–1830) was a French public servant (scientific adviser during the Egyptian expedition, governor, prefect). He developed the general theory for solving problems of heat conduction and vibrations (Fourier series and transforms, diffusion in general). He drew the distinction between conduction and convection (energy carried by material flow), and between thermal conductivity and heat transfer coefficient. Arguably the founder of the modern discipline of heat transfer, or heat transmission, Fourier had great impact on the development of applied mathematics.
- William John Mcquorn Rankine (1820–1872), mechanical engineer from Edinburgh, founded thermodynamics along with Rudolf Clausius and William Thomson (later Lord Kelvin), and wrote the theory of the steam engine and the manuals that gave birth to the thermodynamics books of today.
- Josiah Willard Gibbs (1839–1903) received the first American PhD in Engineering for his thesis *On the Form of the Teeth of Wheels in Spur Gearing* (1863, Yale University) and developed the analytical-geometry representation of the relations between thermodynamic properties of a system at equilibrium.

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.

TABLE I. Highlights in the evolution of thermodynamics (after Ref. 2).

The work line	The heat line
Machines	*Thermometry*
The 12th century: Gunpowder is brought from China to Europe, marking the beginning of the technology of firearms. From Manchester, which as an intellectual environment had played a leading role in the birth of thermodynamics, Osborne Reynolds remarked that "the combustion, in the form of the cannon, is the oldest form of heat engine." A similar view had been advocated earlier by Amontons and Daniel Bernoulli	Galilei's barothermoscope (1592): A glass bulb filled with air and having a downward stem dipped into a pool of mercury
The 13th, 14th, and 15th centuries: The proliferation of water-driven machines, air bellows, water pumps, irrigation, and the draining of mines	Sealed-stem thermometers filled with alcohol; stem calibrated in thousandths parts of bulb volume (Grand Duke Ferdinand II of Tuscany, 1654)
The technology and study of pumps (Stevinus, 1586; della Porta, 1601)	The air thermometer: a volume of air confined by a column of mercury as indicator (Amontons, late 1600s)
The use of mathematical analysis in mechanics, the motion under the influence of gravity, the first instrument for measuring temperature (Galilei, 1623; see also "thermometry" in the adjacent column)	The mercury-in-glass thermometer (Fahrenheit, 1714; the empirical Fahrenheit, Reaumur, and Celsius scales are described in Ref. 2)
The barometer, the orifice velocity of a fluid driven by its own weight (Torricelli, 1644)	*Calorimetry*
A basic understanding of the origins of atmospheric pressure (Pascal, 1648)	The elasticity of a gas, $PV = \text{constant}$ at constant T (Boyle, 1660; Mariotte, 1679; both preceded by Towneley, Boyle's student). The phlogiston theory: Phlogiston is a substance without weight, odor, color, or taste that is contained by all flammable bodies and is given off during burning (advanced by Becher; extended and made popular by Stahl in the late 1600s)
The invention, demonstration, and popularization of the air (vacuum) pump (Otto von Guericke, 1654 and later). Noteworthy is his 1672 book in which he makes popular the idea that the weight of the atmosphere can be put to work: The famous woodcut known as the "Magdeburg hemispheres" shows two eight-horse teams trying to pull apart two 36-cm-diameter hemispheres from which the air had been evacuated—an exaggerated image that invited the work on atmospheric-pumping engines (e.g., Huygens, 1657).	The constancy of temperature during phase change (Newton, 1701; observed also by Amontons)
Captain Thomas Savery builds the first atmospheric engine (1698): The history of the development of heat engines in the prethermodynamics era is continued in Ref. 2.	The foundations of quantitative calorimetry; the concepts of "quantity of heat" and "latent heat"; the discovery of CO_2, called "fixed air" (Black, late 1700s).
From Mechanics to Machine Science	The discovery of oxygen by Priestley (1774), who called it "dephlogisticated air" (later it was named "oxygen" by Lavoisier, who, by explaining combustion discredited the phlogiston theory; Priestley also discovered sulfur dioxide and ammonia)
The *vis viva* theory or the conservation of live force, the method of infinitesimal calculus along with the system of notation that was universally adopted (Leibnitz, 1684; Newton's calculus was published three years later)	The latent heat of fusion of ice and the concept of "specific heat" (Wilcke, 1772, 1781)
The law of universal gravitation, the three laws of motion, calculus presented in geometric terms (Newton, 1687)	Lavoisier and Laplace publish *Memoire sur la chaleur* (1783): a systematic foundation for the science of calorimetry, the heat conservation axiom ("all variations in heat, real or apparent, which a system of bodies undergoes in changing state are reproduced in inverse order when the system returns to its final state"), the calorimetric measurement of specific heat, heat of reaction, and so on. In 1789, Lavoisier publishes *"Traité élémentaire de chimie":* a system of chemistry in which the caloric fluid *(calorique)* is chosen as one of the simple substances or elements. The material or caloric theory of heat becomes established
The conservation of live force in hydraulics, the kinetic-molecular theory of gases (Daniel Bernoulli, 1738)	The gas law $V \sim T$ at constant P (Gay-Lussac, 1802; he also discovered that $\Delta U = 0$at constant T in gases)
The mathematical foundations of inviscid fluid flow (Euler, 1755)	The law of partial pressures in gas mixtures (Dalton, 1805); Avogadro's law (1811). The discovery of "critical temperature" (Cagnard Latour, 1810s)
The gravitational field theory, the mathematics of thermal diffusion (Laplace, 1785 and later)	The approximate character of Boyle's law for real gases; the careful measurement of the specific heat and thermal expansion coefficient of gases, liquids, and solids (Regnault, mid-1800s)
The law governing friction (Coulomb, in a 1781 prize-winning paper)	*Heat Transfer*
The equations of analytical mechanics (Lagrange, 1788)	The proportionality between cooling rate and body-surroundings temperature difference (Newton, 1701)
The foundations of descriptive geometry (Monge, 1795)	Comparative measurement of thermal conductivity (Ingen Housz, 1785, 1789; Count Rumford, 1786 and later)
The beginnings of a science of machines (mechanisms); the "Carnot principle" of avoiding shocks, percussion, and turbulent flow in order to achieve maximum efficiency or continuity in the transmission of mechanical power (Lazare Carnot, 1783; he also defines the concept of "moment of activity," which in 1829 was named "work," independently by Coriolis and Poncelet)	Convection as a principal heat transfer mechanism through clothing (Rumford, 1797; the word *convection* was coined by Prout in 1834)
The *École Polytechnique* is established in 1795: under its influence and through the teachings of some of its first graduates, the study of machines becomes central to engineering education everywhere (e.g., courses by Navier, 1826; Coriolis, 1829; Poncelet, 1829)	The proportionality between heat transfer rate and temperature gradient (Biot, 1804); also the distinction between the thermal conductivity and the heat transfer coefficient (Fourier, 1807)
	Fourier formulates the partial differential equation for time-dependent heat conduction (1807): In today's language, this ranks as the first analytical formulation of the first law (in the context of zero-work processes).

TABLE I. (*Continued.*)

The work line		The heat line
The "dynamic unit" or "dynamode," as the work required to raise 1 kg to a height of 1 m (Hachette, 1811); the "calorie" was defined as the quantity of heat required to raise the temperature of 1 kg of water by 1 °C (Clément, 1826)		The field of heat transfer continues to develop along the pure "heat" line into the late 1900s, when it is reunited with the field of thermodynamics, cf. Figure 1
The criticism of the conservation of caloric doctrine (Count Rumford, 1798 and later; Sir Humphry Davy, 1799)	The "heat" equivalent of "work," or, traditionally, the "mechanical equivalent of heat" (the theoretical line: Mayer, 1842 and later; also Sadi Carnot, 1824; Séguin, 1839; Holtzmann, 1845; the experimental line: Joule, 1843 and later; enriched by Violle, 1870; Rowland, 1879; Hirn; and others)	The "first law" as an integral part of the new science of "thermodynamics" (Clausius, 1850 and later; Rankine, 1850 and later; Kelvin, 1851 and later)

This is why as you read the four portraits about the birth of new physics (above) you may be surprised, because engineering science is not known in comparison with the headlines made daily by physicists and biologists. Yet, the engineering origin of the power to predict nature is real. The heat engine and the laws of thermodynamics (Fig. 1) came into physics from engineering. The impact of engineering on science is so great that most academics today think that Carnot, Rankine, and Gibbs were physicists, not engineers. Why is this? Rankine explained in 1859:

> "…The improvers of the mechanical arts were neglected by biographers and historians, from a mistaken prejudice against practice, as being inferior in dignity to contemplation; and even in the case of men such as Archytas [an ancient Greek philosopher] and Archimedes, who combined practical skill with scientific knowledge, the records of their labours that have reached our time give but vague and imperfect accounts of their mechanical inventions, which are treated as matters of trifling importance in comparison with their philosophical speculations. The same prejudice, prevailing with increased strength during the middle ages, and aided by the prevalence of the belief in sorcery, rendered the records of the progress of practical mechanics, until the end of the fifteenth century, almost a blank. Those remarks apply with peculiar force, to the history of those machines called PRIME MOVERS" (Rankine[8]).

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 development of principles of engineering science (including thermal science) began with the establishment of the modern engineering universities (Paris, 1795; Prague, 1806; Vienna, 1815; Karlsruhe, 1825). This was also the era in which differential calculus was beginning to spread. Even though Carnot and the other pioneers were stating their thermodynamics views with reference to systems of arbitrary size and untold shape and complexity, the second generation of thermodynamicists sought to make its own contribution by using the newly learned language of infinitesimal calculus.

The infinitesimal and microscopic facets of thermodynamics were almost exclusively the contribution of nonengineers (physicists and chemists), at a time when engineers continued on the geometric and macroscopic (finite-size system) path. The emphasis on the frontier shifted to the differential geometry of surfaces that relate the properties of simple systems at equilibrium. Equilibrium thermodynamics (also known as classical, Gibbsian, or analytical) is one lasting result of this emphasis. The steps made in the 20th century away from equilibrium thermodynamics, in what has become known as Irreversible Thermodynamics, or Nonequilibrium Thermodynamics, were also wedded to the infinitesimal approach.

Unwittingly, these steps were a yearning for a return to the realistic (macro) processes and systems contemplated by the pioneers. From the beginning, irreversibility was to be reduced, because every specimen of *homo sapiens* prefers better "performance," which ultimately means easier life, greater wealth, more safety, longer lifespan, and the rest of the "good" things that need no explaining.[1] The giant steps (the new knowledge) illustrated in Figs. 2 and 3 did not occur by chance to people who had neither interest in nor any understanding of irreversibility. On the contrary, from Lazare Carnot (the father of Sadi) through to our own era, reducing irreversibility (or "losses") has been the main issue. That issue is known even better as efficiency increase, performance improvement, getting smarter, or, simply, more knowledge.

Known better does not mean understood better, which is why "smarts" and "knowledge" need an entire book to be explained.[1] Getting smarter is the evolution of the human mind from one generation to the next (and during the growth of each individual) toward a greater ability to effect change. We call this ability "know-how," which means a lot more than possessing stacks of data, also known as "information." Knowledge, in turn, is a lot more than smarts (know-how): it is the precious simultaneity of both smarts and the ability (determination, power, alertness, will, and drive) in the individual to act, to make the change. Knowledge is two human design features present at the same time: idea (design change) and action (implementation of design change), cf. Ref. 1, p. 204. Information is not knowledge.

III. THE "DESIGN" LINE

The first law and the second law are more than 150 years old. They had enormous influence on the science and the

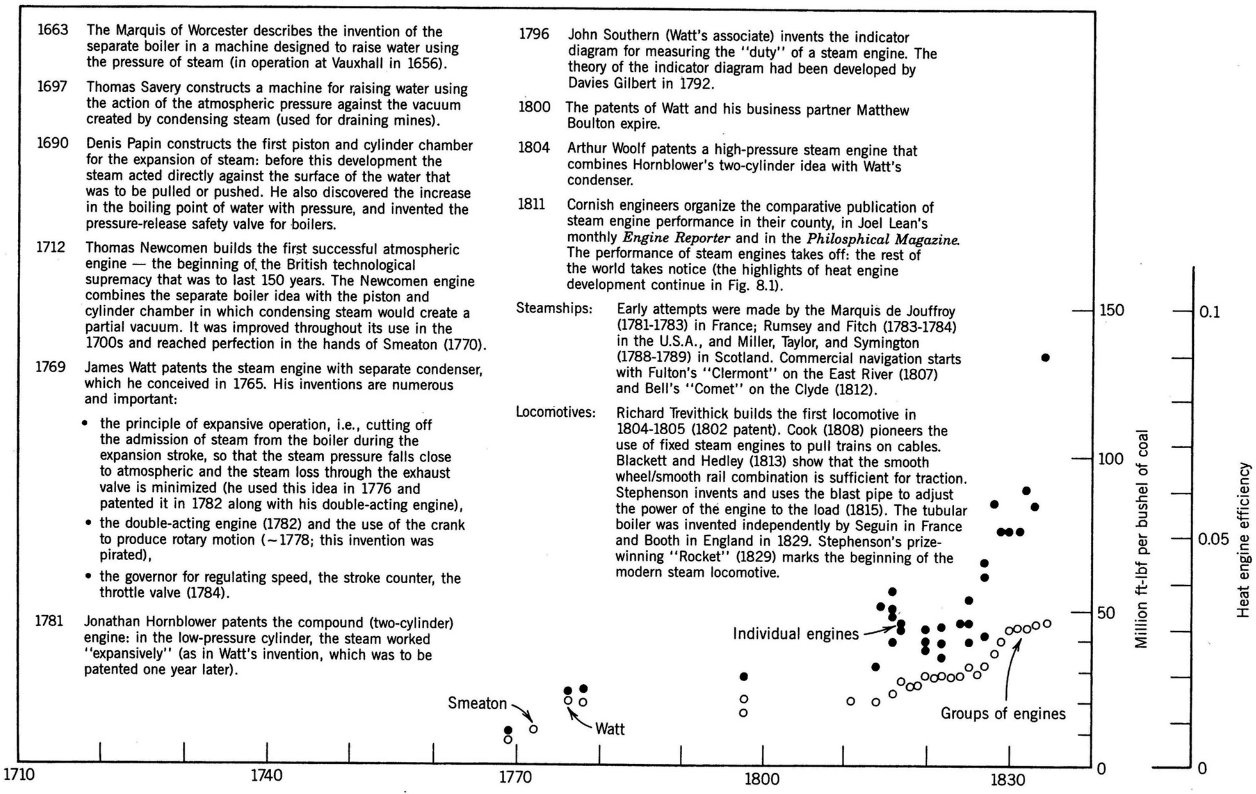


FIG. 2. Highlights in the evolution of steam engines from their inception to the years before thermodynamics. Reproduced with permission from Bejan, *Advanced Engineering Thermodynamics*, 4th ed. (Wiley, Hoboken, 2016). Copyright 2016 John Wiley & Sons.

vocabulary that emerged since the 1800s. 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.[29–60]

From the beginning, the science of heat engine 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). Read also Rankine's quote in Section II, which is entirely about improving performance.

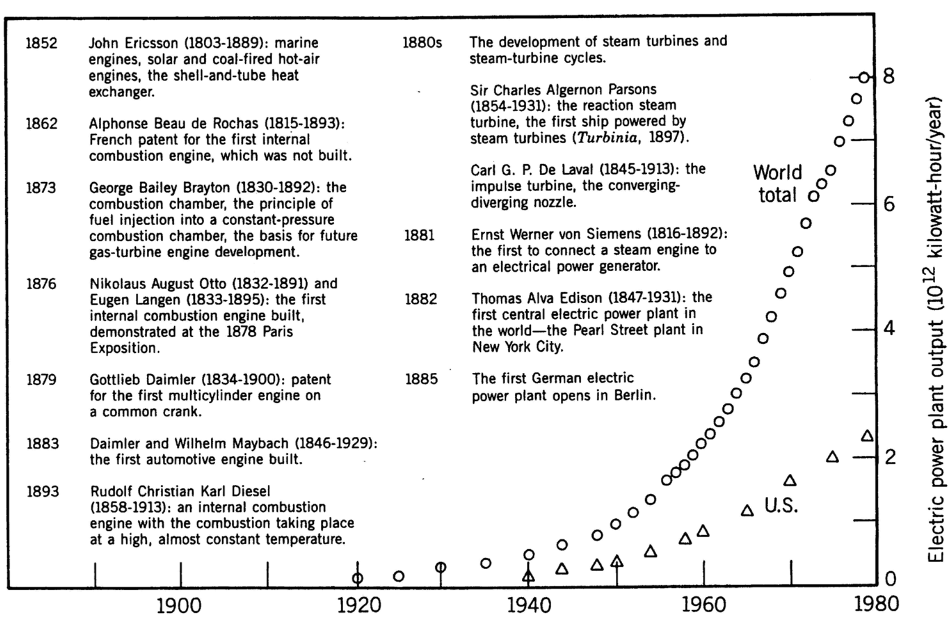


FIG. 3. Highlights in the evolution of power generation and power technology, from the birth of thermodynamics to the contemporary era. Reproduced with permission from Bejan, *Advanced Engineering Thermodynamics*, 4th ed. (Wiley, Hoboken, 2016). Copyright 2016 John Wiley & Sons.

Some people say that thermodynamics has not changed since Carnot, and they would be correct if by thermodynamics they mean just the two laws. In reality, the history of the body of thermodynamics is much larger, newer, and richer, which is why every thermodynamics textbook is "thick" because of lessons of how to make changes in system flow configuration in order to improve performance.

Research in thermodynamics 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. Before the constructal law[1,40,45,61–63] (see also Section VI: The arrow of time) there was no law of physics to demand the search for changes in configuration, which lead to greater performance, but this work went on unquestioned across the board, because its results were intuitively good and, like all science, necessary and useful. Here then are the main milestones along the performance and design line.[64,65]

The concept of "useful work" emerged very early in the evolution of thermodynamics. It followed from the first theoretical breakthrough regarding performance, namely, the first law and second law account for the performance of a heat engine executing a cycle. In the limit of ideal (reversible) operation, the heat engine would deliver to its environment the work W_{rev} based on the heat transfer Q_H received during the cycle while in contact with the high temperature reservoir T_H and the low temperature reservoir T_L. This work output

$$W_{rev} = Q_H(1 - T_L/T_H), \tag{1}$$

is the *useful* work associated with three features of the heat engine as a closed system: Q_H, T_H, and T_L. The same quantity as W_{rev} is known as the exergy transfer (E_Q) associated with the heat transfer Q_H and the T_H source, relative to the ambient T_L, namely

$$E_Q = Q_H(1 - T_L/T_H). \tag{2}$$

This quantity is particularly useful in the thermodynamic analysis of a combustion chamber that drives an engine, where a single high temperature is not evident. The first law and second law analysis of the combustion process delivers the heat transfer from the combustion chamber (Q) and the exergy output associated with the combustion process (E_Q) relative to the ambient temperature level. Next, by using Eq. (2) and writing

$$E_Q = Q\,(1 - T_L/T_f), \tag{3}$$

we define the unique high temperature T_f, which is the effective temperature of the combustion chamber as a source of exergy.[2] Because Eqs. (1) and (3) have the same form, the analysis of heat engine cycles driven by combustion is covered by the same analysis as for heat engines driven by postulated heating from a known (but unavailable) temperature "reservoir."

In reality, irreversibility is present during any cycle executed by a heat engine system. The actual work output W is smaller than W_{rev}, and the difference ($W_{rev} - W$) is the lost work, or the destroyed (dissipated) portion of the useful work. Gouy[66] and later Stodola[67] showed that the lost work is a multiple of the entropy generated during the cycle, namely

$$W_{rev} - W = T_L S_{gen}, \tag{4}$$

where

$$S_{gen} = Q_L/T_L - Q_H/T_H, \tag{5}$$

where $Q_L = Q_H - W$, which has become known as the Gouy–Stodola theorem.[2]

According to Kestin,[68] the concept of useful work can be traced to early pioneers such as Maxwell.[69] The same concept is known as useful energy,[66] available work,[70] availability,[71] and exergy.[70] The associated concept of *destroyed* useful work has become the thermodynamic currency for evaluating the opportunity for improving the performance of any system (closed and open) that executes any process (steady, unsteady, and cycle). Through changes in the flow architecture of the system, it is possible 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.[2,64,65,72] Alternatively, the method is known as exergy analysis and the minimization of exergy loss, or destruction.

During the second half of the 20th 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,[1,29–60] the common-sense concept of "cost" is accepted.[73] 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.[64]

In thermodynamics today, we learn to apply mass and energy balances and, increasingly, entropy and exergy balances. Then, on the basis of known descriptions and specifications, we learn to calculate the size, performance, and cost of heat exchangers, turbines, pumps, and other components. These activities are important, but the scope of design is much wider. Design is primarily system oriented and the objective is to effect a design solution: to devise a means for accomplishing a stated purpose subject to real-world constraints.

Design requires synthesis, a holistic view: selecting and putting together components to form a smoothly working whole.[64,74] Design also often requires that principles from different disciplines be applied with a global objective, for example, principles from thermodynamics, heat transfer, and mechanics. Moreover, design usually requires explicit consideration of economics, for cost is almost invariably a key issue. Finally, design requires optimization techniques that continue to evolve, multiply, and improve, from the applied mathematics of the early 1800s to the computational methods and software packages of today.

To optimize means to opt, to make choices.[75] It does not mean to take the derivative of a continuous function and set it equal to zero. The etymological definition of "to optimize" (to opt) serves to break out of the rut of thinking of derivative based optimization methods. Additional support for the correct meaning of optimization comes from global optimization methods that often reveal topological jumps in design by using various sampling methods such as genetic algorithms.

To conduct a complete and successful optimization of an energy system, designers apply principles of engineering thermodynamics, fluid mechanics, heat and mass transfer, economics, and mathematics, in addition to their experience and intuition. They must also be thoroughly familiar with the system being designed and should understand all technological options available and the interactions both among the system components and between thermodynamics and economics. Hunches and luck can be helpful in design activity.

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. Advances in computational fluid dynamics and heat transfer have facilitated and expanded the reach of the evolutionary design process. Flows that are usually the subject of imagination are now visualized by means of heatlines,[76–78] in the same manner that the imagined fibers of a flowing fluid body are visualized with streamlines. The conversion of heat into work and the thermodynamic temperature scale are now visualized with the T–Q diagram of temperature versus heat interaction,[2,65,79] shown here in Figs. 4–6.

The impact of an effective mathematical model on design simulation and optimization outcome cannot be overemphasized: A good model can make optimization easy, whereas a poor one can make *correct* optimization difficult or impossible. In any case, the quality of the optimization results cannot be better than the quality of the mathematical model used to obtain the results. Worth keeping in mind is that modeling and mathematical analysis are not theory. Modeling is descriptive (empiricism), while theory is predictive. A model is a simplified facsimile of an observed object. Mathematics is a compressed (concise) language for expressing features of the model.

The application of the thermoeconomics evaluation techniques improves our understanding of the interactions among the system variables, and generally reveals opportunities for design improvements that might not be detected by other methods. This activity has developed into the subfields of exergy analysis,[80–85] destruction (loss of useful energy), entropy generation minimization,[65,86–100] and thermoeconomics, or exergy based cost minimization.[64,80,101–107]

The optimization of an energy system seldom leads to a unique solution corresponding to a global mathematical optimum. Rather, very good alternative solutions may be feasible. Different solutions developed by different design teams may be equally acceptable and nearly equally cost effective. As a rule, the more complex the system being optimized, the larger the number of acceptable solutions. This is how "diversity" emerges naturally by invoking one, two, or three universal principles. We see diversity every time athletes break speed records.[45,57,58] The speed is essentially the same, but the winners are different.

IV. ONE LAW FOR ONE UNIVERSAL NATURAL TENDENCY

Thermodynamics is brief, simple, unambiguous, and improving. Yet, confusion reigns in the field, and this is where the self-correcting happens, naturally. The name "entropy" is pasted on new things, without respect for its proper definition in thermodynamics (Landsberg,[108] Denbigh,[109] Styer,[110] Lambert,[111] and Muschik[112]). New authors bow to their own maximum or minimum principle, even when it contradicts logic, not just thermodynamics. Why the logic, because minimizing cannot be the same as maximizing, minimizing resistance cannot be the same as maximizing resistance, and minimizing entropy generation cannot be the same as maximizing entropy generation. Because of the word "entropy," many believe that entropy

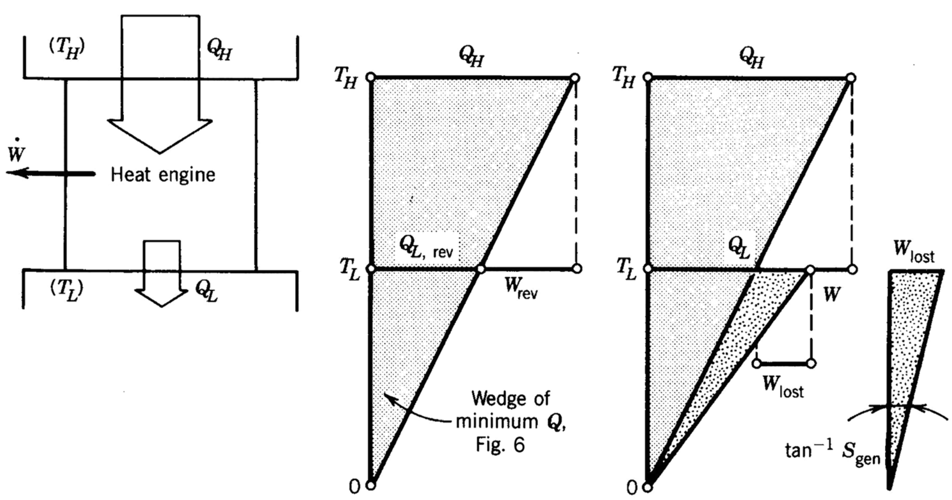


FIG. 4. Temperature–energy interaction diagram (the T–Q graphic method) for a heat engine operating in cycles or steady state.[65] Reproduced with permission from Bejan, *Advanced Engineering Thermodynamics*, 4th ed. (Wiley, Hoboken, 2016). Copyright 2016 John Wiley & Sons.

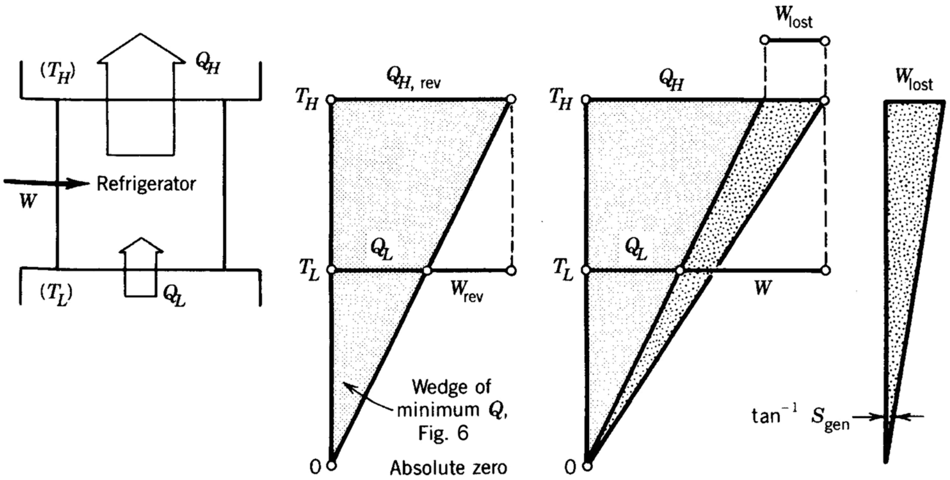


FIG. 5. Temperature–energy interaction diagram (the T–Q graphic method) for a refrigerator operating in cycles or steady state.[65] Reproduced with permission from Bejan, *Advanced Engineering Thermodynamics*, 4th ed. (Wiley, Hoboken, 2016). Copyright 2016 John Wiley & Sons.

generation *minimization* and *maximization* are covered by the second law, which is false.

Another misconception is due to the thermodynamics notion that for a closed system that cannot experience a heat interaction with its environment (a special example of this kind is an isolated system) the second law states that the system entropy inventory (a property) increases in time, while changes occur inside the system. Because of this, many believe that the second law accounts for organization, evolution, life, death, and the arrow of time. This is wrong. Here are the definitions of system, closed, adiabatic, and isolated.

The thermodynamic system (in general) is the region in space, or the amount of matter selected by you the thinker for the purpose of analysis. The thermodynamic system is defined unambiguously by the boundary selected by you. The boundary is an imaginary surface, and because a surface has zero thickness, the boundary is not a system. The universe is made of only two systems, your system and the environment of your system.

A closed system is a thermodynamic system, the boundary of which is impermeable to mass flow. The mass inventory of a closed system is fixed.

An open system is defined by a boundary that permits the flow of mass. The mass inventory of an open system may change. A closed system is a special case of open system.

The adiabatic closed system is a special case of closed system because it cannot experience heat transfer. The isolated system is a special kind of adiabatic system. An isolated system cannot experience heat interactions and work interactions with its environment.

From the general to the special, the system types reviewed above are aligned as open-closed-adiabatic-isolated. Many people and many authors confuse closed system with isolated system and adiabatic system. Pinker[113] just published an essay with several assertions that are questionable in view of Secs. IV–VI. This is why thermodynamics must be taught correctly, respected, and fiercely defended.

This review is a good opportunity to take a fresh look at nature, at the physics, and at the science of all the natural things that "happen." Words are useful because they have meaning. This is why it is necessary to define the terms of the discussion unambiguously.

The observation that certain things happen innumerable times the same way is one natural tendency, and that represents one *phenomenon*. The *law* of physics is the compact

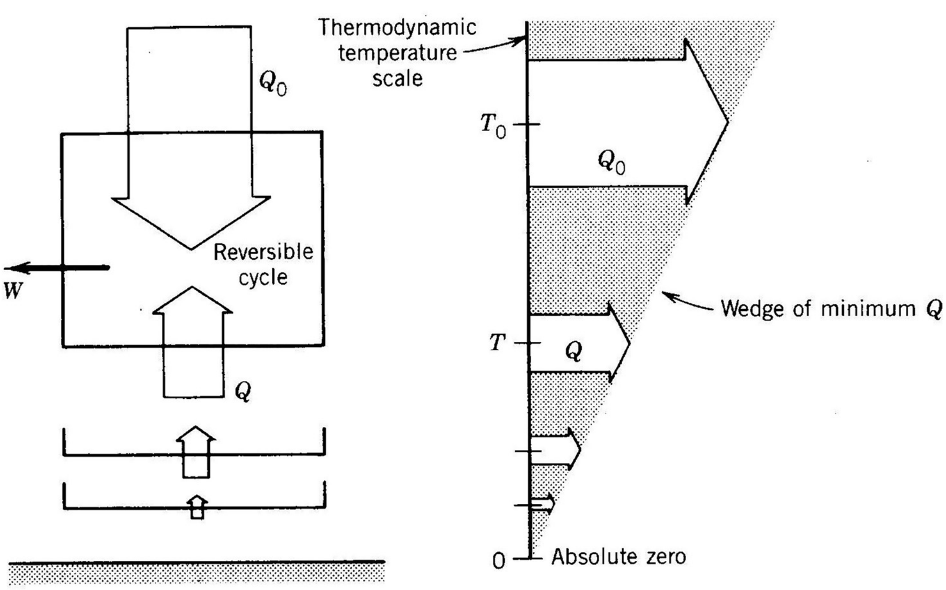


FIG. 6. Wedge of minimum-Q diagram: the measurement of the heat transfer Q using a heat engine that executes a reversible cycle: from this the construction emerges the thermodynamic temperature scale T. This graphic construction was proposed in the first edition (1988) of Ref. 2, as an application of the T–Q graphic method proposed in 1977,[65,79] cf. Figs. 4 and 5. Reproduced with permission from Bejan, *Advanced Engineering Thermodynamics*, 4th ed. (Wiley, Hoboken, 2016). Copyright 2016 John Wiley & Sons.

statement (text, or formula) that summarizes the innumerable observations of the same kind, the one phenomenon. To rely on the law to experience a purely mental viewing of how things *should be* (i.e., to predict observations, a phenomenon) is *theory*. To predict (to do theory) is the opposite of to observe (to do empiricism). The law is one, while the theories are as numerous as the settings in which the law is invoked.

Thermodynamics is the physics of three distinct (self-standing) phenomena, which are summarized today in three distinct laws (cf. Fig. 1):

The phenomenon covered by the first law of thermodynamics is the "what goes up must come down" from old mechanics. Today, we recognize this more generally as the *conservation of energy*, from kinetic energy to potential energy when a body is thrown upward, to the energy flow (from heat into work) through a thermodynamic system such as a power plant, or from work into heat in a purely dissipative system (PDS) such as a brake, or an animal walking.

The phenomenon covered by the second law is the "one way flow," such as the flow of water under the bridge. Today, we recognize this distinct natural tendency as *irreversibility*. Every flow, by itself, proceeds from high to low. Fluid flows through a duct from high pressure to low pressure. Heat leaks through an insulation from high temperature to low temperature. If you do not know beforehand which is the high and which is the low, then the direction of the flow will tell you. Why, because it is the law, and any thermodynamic system obeys the law.

The phenomenon covered by the constructal law is the *evolution of configuration* in freely morphing thermodynamic systems. This is the phenomenon of life and evolution in the broadest possible sense, as physics. The 1996 statement of the constructal law is:

> "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."[1,40,45,61–63]

If the reader has a particular flow system in mind, say, air flow in lungs or electricity in lightning, then the reader can express the evolutionary design toward easier access in terms of locally appropriate variables and units. Yet, the fluid flow terminology of the lungs has no place in the analysis of the flow of electricity as a lightning tree, and vice versa. What is the same in both examples is the constructal law, which is a first principle for a self-standing phenomenon: the evolution of design toward easier access, through changes in flow configuration in a finite-size system. Following its original statement in words, the constructal law was formulated mathematically in several ways.[114] In the constructal theory of why celestial bodies should be hierarchical in sizes and numbers (not one size),[115] we showed that the constructal law can be falsified in real time, to be verified as correct, in accord with the test prescribed by Ellis and Silk.[116]

To review the constructal-law field is not the objective here: for constructal reviews published by other authors see Basak,[117] Chen,[118] Miguel,[119,120] Reis,[41,121,122] Ventikos,[123] Wang,[42] Lucia,[43,44] Kremer-Marietti,[124] Kalason,[125,126] Bachta and Kremer-Marietti,[127] Queiros-Conde and Feidt,[128] Rocha,[129] Lorenzini *et al.*,[130] and Pramanick.[131] Observations of the constructal-law phenomenon are everywhere: inanimate systems,[56,132–140] animate systems,[32–35,40–45,55] city traffic evolution, aircraft evolution,[1,141,142] and technology evolution in general.[143–148] These observations reveal the arrow of time in nature, which points from existing flow configurations to new configurations through which the flowing is easier. Not the other way. Why, because it is the law, and any system obeys the law.

The first law, second law, and constructal law are "first principles," because each law cannot be derived from existing laws. They unite the animate flow systems (the biosphere, animals, vegetation, organs, cells, humans, and societies) with the inanimate systems, which are much older and more prevalent in the universe (river basins, lightning, lava, winds, ocean currents, plate tectonics, and magma). They unite the "natural" with the "artificial." The natural are all the animate and the inanimate systems. Artifacts and niche construction are also natural because they are objects made by animals and humans in order to magnify the power of humans. Any such object (including ideas, learning, and science) is an empowering extension, an add-on to the natural individual.

People like to say that nature is complicated. Not if you see nature from thermodynamics! Nature is the simplest thought imaginable, because nature consists of only two systems, your system (the portion selected by you for contemplation) and the rest, which is also selected by you (the environment). If your chosen system generates power in order to move through its environment, then the world that you contemplate is an "engine and brake" whole (Fig. 7). Others may contemplate other systems that generate power and movement (waterfalls, animals, vegetation, etc.). For all the thinkers together, the same world as yours is an endless collection of intertwined (embedded) engine and brake flow systems. The extreme simplicity of nature is revealed by the engine and brake flow configuration (natural convection) shown in Fig. 8.

The physical effect of evolving design is more movement and greater access for all movers. This is what all "Maxwell's demons" achieve,[149] and this lesson is especially recommended to students of thermodynamics. This is the complete design of all animate and inanimate flow systems, from water flowing in river basins, to animal locomotion and urban traffic, and atmospheric and oceanic circulation.

V. EVOLUTION

The physics meaning of life and 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

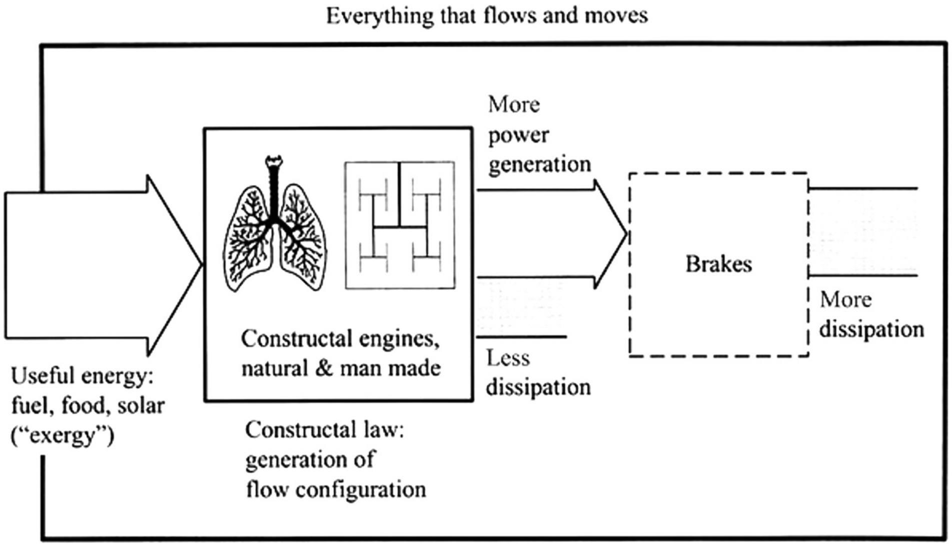


FIG. 7. The engine and brake flow configuration of nature is represented by the flow of useful energy into the earth (the large rectangle), the partial destruction of this flow in the animate and inanimate engines (the larger square), followed by the complete destruction of the remaining useful energy stream in the interactions with the environment (the brakes shown in the smaller square). In time, all the flow systems exhibit the constructal-law tendency of generating "evolving designs," and this time arrow means less dissipation in the engines and more dissipation in the brakes. Reproduced with permission from Bejan, *Advanced Engineering Thermodynamics*, 4th ed. (Wiley, Hoboken, 2016). Copyright 2016 John Wiley & Sons.

(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 (free morphing) in geometry, which occurs one way, in a goal-oriented direction in time (see Section VI). 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 grater access to what flows in it.

Evolution has come under increased scrutiny during the past three decades, because of the questioning of the rule of chance and evidence that suggests an evolutionary purposeful direction in design change.[29–60,149–153] Similar but not the same as evolution is the growth of a flow architecture that spreads into its available space: populations, tumors,

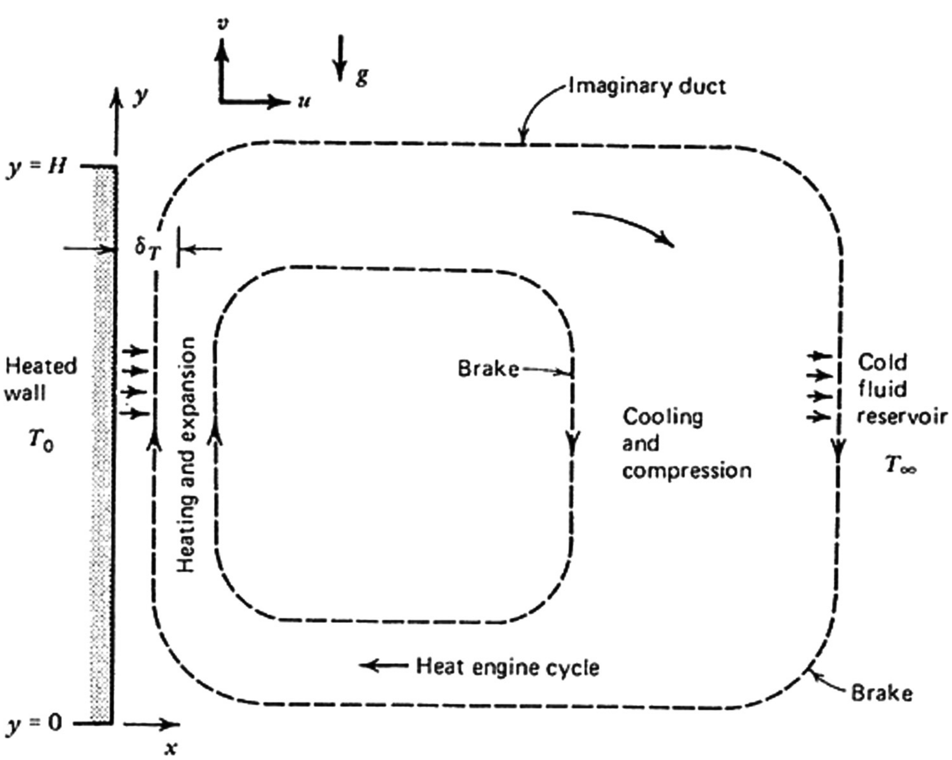


FIG. 8. The engine and brake flow configuration of the atmosphere and the hydrosphere. Any fluid packet undergoes a cycle of heating–expansion–cooling–compression, which is the Rankine power cycle. The power that would be produced by the system (fluid packet) undergoing the cycle shown in this figure is destroyed instantly and completely by viscous dissipation of power in the brakes, which are the relative-motion interfaces between the flowing layers of fluid. Reproduced with permission from Bejan, *Convection Heat Transfer*, 4th ed. (Wiley, Hoboken, 2013). Copyright 2013 John Wiley & Sons.

river deltas, and mines for oil and minerals. The growth of a spreading or collecting flow architecture is the universal S-curve phenomenon: slow in the beginning, faster toward a peak growth rate, and then slow again. It was shown that S-curve phenomena are manifestations of the universal tendency toward architectures for greater flow access, which is covered by the constructal law.[139,154]

Evolution (the "moving picture" of design change) must not be confused with end design and "destiny" (the still image). The evolution phenomenon is without end. There have been visions of end-design in science, expressed as optimality statements:

(i) Minimum entropy generation and maximum efficiency are used commonly in engineering and biology (Reis[155]).
(ii) Maximum entropy generation is being invoked in geophysics (Paltridge[156]).
(iii) Maximum "fitness" and "adaptability" (robustness and resilience) are used in biology (Hoppeler and Weibel[31]).
(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, etc.
(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 tissue and bones. Most authors do not even question the axiom, instead they speak as if everybody knows.
(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.

The individual phenomena covered by optimality statements are manifestations of the universal physics phenomenon of evolution, which is covered by the constructal law. Even though the optimality statements are contradictory, local, and disunited on the field of evolution in nature, they demonstrate that the interest in placing evolution phenomena deterministically in science is old, broad, and thriving. Reviews of the progress being made with the constructal law (e.g., Basak[117] and Ellis and Silk[116] and Reis[41,122,155]) show that the diverse phenomena addressed with the *ad hoc* statements (i)–(xii) are manifestations of the single natural tendency that is covered by the constructal law.

One example is the overt contradiction between minimum and maximum entropy generation [(i) and (ii) above], which was resolved based on the constructal law. As shown in the caption of Fig. 7, the flowing (the live) nature is composed of systems that move as engines connected to brakes. 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 increase (maximum) or the decrease (minimum), or the fact that the "engine + brake" constitution of nature brings them together. The principle is the evolution of all "engine" configurations in the constructal-law direction in time, and the symbiotic evolution of "brake" configurations in the same direction. The constructal law is universally valid precisely because it is not a statement of optimality and end design (Reis[122,155]).

VI. THE MOST COMMON MISUNDERSTANDINGS

Some of the misunderstandings today revolve around the second law and the thermodynamic property entropy, which is a derived property because it cannot be measured by experiment directly. Thermodynamic properties are of two kinds: *measurable* (pressure, temperature, volume, and specific heat), and *derived* by combining the measurements with the first law and the second law (energy, enthalpy, and entropy). Here are a few claims we often hear, and some immediate remarks as an invitation to the reader to question such statements:

A. The second law explains evolution

This is not true, because evolution means change in flow configuration over time, while the second law refers to *any* system, to a black box without specified configuration, changing or not changing. We also hear that the end-design idea of maximization of entropy generation (ii) is a "law" of maximum entropy production, which follows deductively from the second law of thermodynamics. This is false. Here is the correct statement of the second law, made by two of its original proponents:

> 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.

Note that a new law does not have to be stated in mathematical terms (e.g., thermodynamic variables and units). For example, the second law of thermodynamics and the constructal law were stated in words, as a mental viewing, not mathematically.

B. How can entropy be measured?

What can be measured is the *change* in the entropy inventory of a closed system, the change relative to a reference state. Entropy change from state 1 to state 2 is the name for the integral of $\delta Q/T$ during a reversible process from state 1 to state 2, where δQ is the infinitesimal heat transfer from the environment to the system during the process, and T is the contact temperature (kelvin) of the system, at the spot crossed by δQ (Muschik[157]). 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.

C. The arrow of time is the second law

Such statements have no basis in thermodynamics. The second law says nothing about "form." Many believe that the arrow of time in nature is imprinted on one-way (irreversible) phenomena, and is accounted for by the second law of thermodynamics. This is wrong. That arrow of time points toward "nothing moves," and nothing moves means death,[1] not the evolving nature all around us. The correct arrow of time is painted much more visibly on *live* phenomena: the occurrence and change (evolution) of flow organization throughout nature, animate and animate.

The arrow of time of evolutionary design phenomena is essential, because "time" is a fundamental property of nature, and is constantly under debate in modern physics. The arrow of time of evolution is the statement of the constructal law, cf. Section IV.

D. Disorder and entropy

In response to a previously published article, Moran and Shapiro[158] correctly pointed out that the use of disorder to explain macroscopic thermodynamic principles is inappropriate and misleading. They criticized a host of other statements such as "the greater the entropy, the greater the losses, waste, and environmental impact" and that a wooden log "contains energy that is neatly organized."

E. Disorder is increasing

Observed is also the opposite, which is the ubiquitous phenomenon of self-organization, cf. (i)–(xii) in Section III. Order is in the eye of the observer. Where many see the trivial (diversity), the few see the subtle (order, organization, and principle).[159] The second law says nothing about "disorder," cf. Clausius' and Kelvin's statements above. 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.[160] This is the core idea of statistical mechanics, which is a more recent, self-standing field.

To assume a swarm of particles in a closed box is to throw away the "any system" power of thermodynamics, which can be regarded as basis for phenomenological thermodynamics. The any-system is the most general, and the box with bouncing particles is the extremely special, the local, the particular system with a postulated configuration.

F. Topology

Topology is often used to describe design in nature. This term is inappropriate. Webster's dictionary teaches that topology is defined either as "The study of a specific object, entity, place, etc." or "The study of those properties of geometric figures that remain unchanged even under distortion." Evolutionary design is neither. Evolution is not about the unchanged. It is about the phenomenon of dynamic flow architecture, morphing while flowing.[1]

G. More flow

Some confuse the constructal law with an assumed natural evolutionary trend with toward "more flow," which is not correct. The natural tendency is to evolve freely into flow configurations that offer greater access to what flows, not more flow.

H. The laws of thermodynamics hold only for closed systems

This is not true because the laws of thermodynamics are universally valid, for any system, closed or open. The confusion is understandable because during the birth of thermodynamics at the confluence of the "heat" and "work" lines (Fig. 1) 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 (Fig. 4). The two laws were stated initially for closed systems. They were generalized to apply to open systems at the end of the 1800s, chiefly because of Gustav Zeuner and the advances in locomotive design evolution. In fact, none of the advances made in the technologies that generate and use power today would have been possible without the correct application of the first law and the second law to systems that are modeled as open, which is the most general model. As reference for the law statements cited later in this section, the first law and the second law for any open system are

$$\frac{dE}{dt} = \dot{Q} - \dot{W} + \sum_{in} \dot{m}h - \sum_{out} \dot{m}h, \tag{6}$$

$$\frac{dS}{dt} \geq \sum_{i} \frac{\dot{Q}_i}{T_i} + \sum_{in} \dot{m}s - \sum_{out} \dot{m}s, \tag{7}$$

and are complemented by the law of mass conservation,

$$\frac{dM}{dt} = \sum_{in} \dot{m} - \sum_{out} \dot{m}. \tag{8}$$

In these statements, the mass flow rates (in, out) are $\dot{m}$, the heat transfer rate into the system is $\dot{Q}$, the work transfer rate (power) out of the system is $\dot{W}$, and (E, S, M) is the instantaneous inventory of energy, entropy, and mass of the system. Carried across the boundary by the inflows ($\dot{m}_{in}$) and outflows ($\dot{m}_{out}$) are streams of enthalpy ($\dot{m}h$) and entropy ($\dot{m}s$), where h and s are the specific (per unit mass) enthalpy and entropy of the material that passes across the boundary. Noteworthy are the terms $\dot{Q}_i/T_i$ in Eq. (7), which represent the rate of entropy transfer associated with the heat transfer rate $\dot{Q}_i$ that crosses the boundary at the spot that has the thermodynamic temperature T_i.

I. The laws of thermodynamics pertain to equilibrium states

This is contradicted by the presence of the inequality sign in the second law, Eq. (7), which refers to the *irreversibility* of flows inside the system and between system and environment. Flows happen because of the temperature and pressure differences that drive the flows. Such systems are not in equilibrium; in fact, all the systems modeled after nature and engineering are in nonequilibrium states, which is why nonequilibrium (or irreversible) thermodynamics is a common title for contemporary thermodynamics.[161]

J. Thermodynamics should be called thermostatics

This is contradicted by the d()/dt terms on the left side of Eqs. (6)–(8). The "any" system that obeys the laws is capable of changing in time, in fact, most of the thermodynamic systems analyzed in applied physics, engineering, and natural sciences are evolutionary, time dependent, and dynamic, not static.

K. Conservation reduces fuel consumption

This too is contrary to physics, even though it is heard often and never questioned in policy debates regarding the energy future. Conservation of fuel in a particular power plant occurs when the design changes and the energy conversion efficiency of the plant increases. Why society takes such improvements as invitation to burn even more fuel, not less, is known as Jevon's paradox.[162] The paradox is explained[1,163] by the urge of every member of society to have more access for movement, which means to have access to more power, and when more power becomes available the liberated movement calls for even more power and fuel.

L. Analogy between heat and work

Consider the analogy between heating a solid body and charging an electrical capacitor,[164] or stretching a spring. Such claims violate the second law, as I show next. The statements for the first and second laws of thermodynamics for a closed system can be read of Eqs. (6) and (7) by deleting the $\dot{m}$ terms.

First, a solid body (mass m, specific heat c) is a closed system that is constituted in such a way that it can experience heat transfer (heating, cooling, δQ) but is incapable of experiencing work transfer (δW) of any kind. Such a system is a *purely thermal system* (PTS), and the first-law statement for any process (a change, from state 1 to state 2) executed by a PTS requires that

$$Q_{1-2} = U_2 - U_1, \quad (\text{PTS}), \tag{9}$$

where $U_2 - U_1$ is the change in the internal energy of the system, which is a system property, a function of state. The PTS is a special class of closed systems.

Second, a spring or an electrical capacitor is a closed system that is constituted in such a way that it can experience work transfer, but not heat transfer. See the entirety of Table II. Other closed systems that can experience only work transfer are an accelerating mass, a rising weight (which can be viewed as a constant-force spring), and many more. Such systems are *purely mechanical systems* (PMS), as a special class of closed systems. Any process (1–2) executed by a PMS obeys the first law statement

$$-W_{12} = (E_2 - E_1)_i, \quad (\text{PMS}), \tag{10}$$

where $E_2 - E_1$ is the change in the energy inventory of the PMS, and i indicates the type of PMS.

Third, the energy change experienced by a PMS is macroscopically identifiable in terms of observable properties of the closed system, such as speed (V), deformation (x), height (z), and charge (q), cf. Table II.

Charging a capacitor is analogous to stretching a spring. Both processes require 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. In both examples, the energy change is proportional to the change in the square of the displacement. One PMS is analogous to another PMS.

No PMS is analogous to a PTS such as a solid body that is being heated. The fallacy of the PMS–PTS analogy is made evident by the second law of thermodynamics. Any heat transfer interaction (δQ) is accompanied by entropy transfer ($\delta Q/T$), where T is the thermodynamic temperature of the boundary spot crossed by δQ, whereas any work transfer interaction is accompanied by zero entropy transfer. Note the absence of work terms in Eq. (7) and the second law for closed systems executing any process 1–2

$$S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}, \quad (\text{PTS}), \tag{11}$$

$$S_2 - S_1 = 0, \quad (\text{PMS}). \tag{12}$$

Here, $S_2 - S_1$ is the change in the entropy inventory of the system, which is a system property, a function of state.

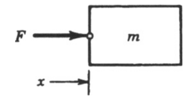
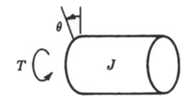
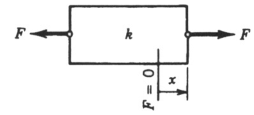
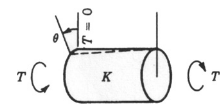
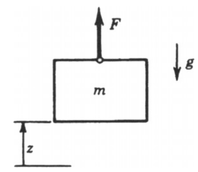
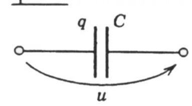
That heat and work are not analogous is even more clear in closed systems that are incapable of storing energy during any process, for which the first law and the second law reduce to

$$Q_{12} - W_{12} = 0 \quad (\text{PDS}), \tag{13}$$

$$Q_{12} \leq 0, \quad \text{or} \quad W_{12} \leq 0. \quad (\text{PDS}). \tag{14}$$

These are *purely dissipative systems* (PDS): during any process they convert work input into heat output. The conversion is one way. While for a PDS the first law (13) declares heat transfer and work transfer equal, the second law (14) declares them as different, work *in* and heat *out*. Dissipation, or irreversibility, proceeds one way. The one-

TABLE II. Purely mechanical systems: their macroscopic forms of energy storage and work interactions (after Ref. 2).

Macroscopic forms of energy storage, $(E_2 - E_1)_i$	Constitutive relation	Infinitesimal work transfer, δW	Notation
Kinetic, translational $\frac{1}{2}mV_2^2 - \frac{1}{2}mV_1^2$	$F = m\frac{dV}{dt}$	$-F\,dx$	
Kinetic, rotational $\frac{1}{2}J\omega_2^2 - \frac{1}{2}J\omega_1^2$	$T = J\frac{d\omega}{dt}$	$-T\,d\theta$	
Spring, translational $\frac{1}{2}kx_2^2 - \frac{1}{2}kx_1^2$	$F = kx$	$-F\,dx$	
Spring, rotational $\frac{1}{2}K\theta_2^2 - \frac{1}{2}K\theta_1^2$	$T = K\theta$	$-T\,d\theta$	
Gravitational spring (or constant-force translational spring) $mgz_2 - mgz_1$	$F = mg$	$-F\,dz$	
Electrical capacitor $\frac{q_2^2}{2C} - \frac{q_1^2}{2C}$	$u = \frac{q}{C}$	$-u\,dq$	

way is the universal natural tendency (phenomenon) of irreversibility, which is summarized as the second law.

The heat-work analogy would be perfect if Eq. (9) would look just like Eq. (10), that is, if the function of state $(U_2 - U_1)$ would be identifiable in terms of measurable properties that describe the *macroscopically* visible state of the heated body. The only measurable property of a heated solid body (other than the heat input) is not macroscopic: it is the temperature T, which in thermodynamics today means *thermodynamic temperature* (units K), Fig. 6. The temperature T is measurable because the system is at equilibrium with its environment, or assumed to be in local thermodynamic equilibrium (cf. Muschik and Brunk[165]). The temperature is not like the speed of a bullet, the deformation of the spring, the level of the raised weight, and the separating by force of the (+) charge from the (−) charge, on the two opposing plates of the capacitor.

To make the $(U_2 - U_1)$ of the PTS look analytically like the $(E_2 - E_1)_i$ of the PMS, imagine that the $(U_2 - U_1)$ of the solid body is expressible as $C_{PTS}T_2^2 - C_{PTS}T_1^2$, where C_{PTS} is a constant factor that belongs to the description of the purely thermal system. The PTS–PMS analogy would be complete, but, (i) Is it possible mathematically? and (ii) Is it real, a part of nature?

The answer to the first question is yes, if one imagines that during the heating process represented by Eq. (9), the designer of the heating process has instrumented the heater (i.e., the environment) in such a way that $\delta Q = \alpha T dT$, where α is a constant proportionality factor (units J/K^2) of the heating instrument, and T is the instantaneous thermodynamic (K) temperature of the heated body. In other words, during the heating process, the environment (with you and the heating instrument included) performs two functions, it measures the instantaneous body temperature T, and transfers to the solid body an increment δQ that is proportional to the temperature (kelvin) reached by the body at that moment. The mimicking of the δW expressions for the PMS examples is evident: the $\delta W = -kxdx$ of the spring and the $\delta W = -\frac{1}{C} q\,d\,q$ of the capacitor are replaced by $\delta Q = \alpha T dT$ for the heated body, and consequently Eq. (6) assumes the same analytical form as Eq. (10), for which the $(E_2 - E_1)_i$ formulas are listed in Table II

$$Q_{12} = U_2 - U_1 = \frac{1}{2}\alpha T_2^2 - \frac{1}{2}\alpha T_1^2. \quad (15)$$

Next, consider question (ii). Is the factor α a natural occurrence, or simply the choice made by the environment (i.e., you) in order to invent a $(U_2 - U_1)$ expression that looks like the $(E_2 - E_1)_i$ expressions? This is how you arrive at the answer to question (ii). The α does not belong to the system (the body that is being heated). The α belongs to the other system (the environment, i.e., you), and you can change it. This is why the right hand side of Eq. (15) is not a function of state, and not a thermodynamic property. It is not a physical quantity. It is even less an *extensive* property (with a value proportional to the system size m), because the only way to measure it is by measuring T, which is an *intensive* property, which is a physical measurement independent of system size.

A theory based on the right side of Eq. (15) is impossible, because the word "theory" means a purely mental viewing that is predictive, an image of what and how things *should be* before we look at nature. No such thing is accessible via Eq. (15) mathematics. The heat-work analogy is a mistake, as pointed out independently by a growing number of authors.[166–176] Furthermore, Grazzini and Rochetti[173] concluded that "Entransy does not contain any new information in comparison with a classical analysis of systems using entropy." The same conclusion was published by Oliveira and Milanez.[171]

Mistakes in science are understandable (cf. Section VIII). Yet, to keep publishing the mistake[177,178] after it was identified and corrected in the literature is an entirely different behavior. The direction of this other evolutionary phenomenon is captured by the Portuguese proverb: *A verdade é como a cortiça, vem sempre ao de cima* (Truth is like a cork, it always rises to the surface).[179]

VII. THE PERPETUAL MOTION PRECEDENT

Repeated misunderstandings that have long been corrected in the form of "thermodynamics" have a lot in common with repeated claims of *perpetuum mobile* inventions. The history of *perpentuum mobile* inventions shows the way forward. Two hundred years ago, the *Institut de France* adopted the policy of not accepting any more claims of *perpetuum mobile* inventions (Gillispie[16]). Such inventions had been proven invalid based on the science of mechanics. A clock cannot turn forever, because of friction. To deny review to such claims was not censorship then, and it is not today. On the contrary, it is liberating and encouraging the evolution of science.

What is to be done? The answer is obvious: teach thermodynamics correctly, improve it along the way, make it even more general and powerful, and clean up the misconceptions that tend to arise during the evolutionary design of science.

Just look at the invention sketched in Fig. 9, which was sent to me by a colleague in the late 1980s. I found it so ingenious that I used it as a teaching opportunity ever since (Ref. 2, problem 8.17). What can be more obvious and appealing than this device for the production of mechanical power $\dot{W}$ [watts], from the atmosphere, T_0 [K]? The airstream $\dot{m}$ [kg/s] is used first as heat source in the heater (boiler) of the power plant. The temperature of the airstream drops as it flows through the heater; therefore, the stream is used next as heat sink while flowing through the cooler (condenser) of the power plant. The airstream is finally discharged into the atmosphere. What is wrong with that?

Wrong is the focus on the particular scheme, which is the claim. Wrong is to lose sight of the big picture, the holistic view. It is like watching the hands of the magician, not the whole stage. At fault is modern science education, which is reductionist, and this is particularly the case in thermodynamics. The cure is to step away from Fig. 9, and recognize that on its right edge the $\dot{m}$ loop must complete itself while in thermal contact with the ambient. The "whole" system that contains this complete drawing is a closed system in steady state, with a boundary of one temperature (T_0) and the atmosphere as the environment.

For the whole system, the first law of thermodynamics requires that $\dot{W} = \dot{Q}_0$, where $\dot{Q}_0$ is the heat transfer rate

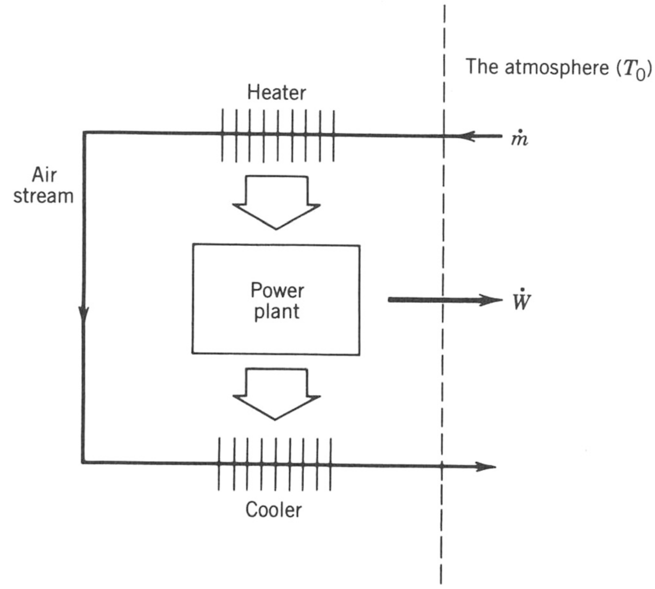


FIG. 9. Power plant with heating and cooling provided by an airstream coming from and returning to the ambient (Ref. 2, problem 8.17). Reproduced with permission from Bejan, *Advanced Engineering Thermodynamics*, 4th ed. (Wiley, Hoboken, 2016). Copyright 2016 John Wiley & Sons.

between system and environment. If the inventor is right, then power is produced ($\dot{W} > 0$) and heat must be transferred from the atmosphere to the system ($\dot{Q} > 0$). This flow direction is a violation of the second law of thermodynamics for this class of systems: closed, thermal contact with only one temperature reservoir, and operating in steady state or an integral number of cycles.

We have rediscovered here that the whole can be, at best, a purely dissipative system, cf. Eqs. (13) and (14), which show again that heat transfer is not analogous to work transfer. The heat-work "analogy" is a mistake on the same level as a perpetual motion "invention."

VIII. THE SELF-CORRECTING NATURE OF SCIENCE

Figure 1 is a concise summary of the two evolution aspects of thermodynamics covered in this review, while Table I is a detailed summary of the human events, times, names, and places. This evolutionary design phenomenon has no end. It has already placed biology in physics,[1,32–35,40–45,55,117,123] and it is now placing economics in physics.[180–183]

What works is kept, as an add-on to the architecture that was flowing before.[1] What is false is swept aside, and forgotten. This is the evolutionary "morphing" design that science is (Figs. 10 and 11).

This is also why every once in a while the scientific community is presented with a reality check, a new bird's-eye-view that is suddenly useful as a guide to the new generations. Revisionism is checked, authority is questioned, mistakes are corrected, and this way a renewed appreciation of the "classics" empowers the new generations.[186] This happens sometimes in a spontaneous paper, a new perspective, a new review, and a new book. Researchers, authors, university administrators, national academies, publishers, and

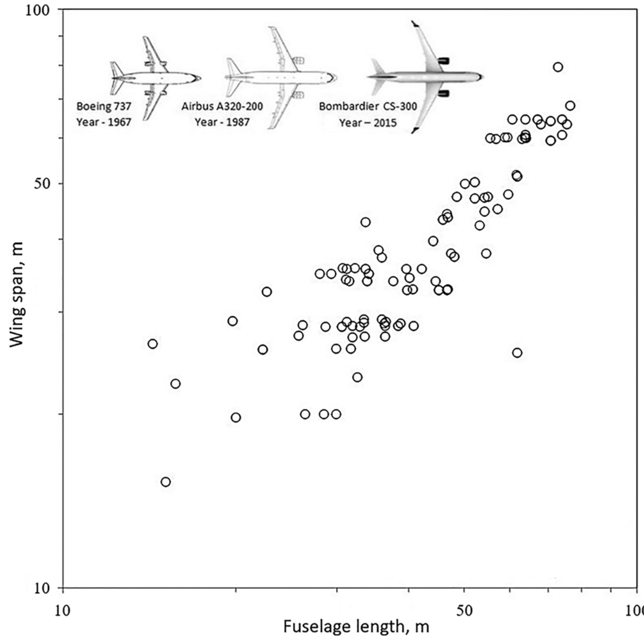


FIG. 10. The evolution of the shapes of airplanes during the 60-year history of commercial jet aviation. The time arrow points from the lower left to the upper right. In the beginning, the aspect ratio (wing span)/(fuselage length) varied among airplane models. Over time, the designs that prevail are exhibiting the same aspect ratio: the wingspan is essentially equal to the fuselage length, just like in animal fliers of all sizes.[141] Reproduced with permission from J. Appl. Phys. **116**, 044901 (2014). Copyright 2014 AIP Publishing LLC.

especially editors learn from this. The stream flows better after the tree log is swept out of the way.

Mistakes happen. As the paleontologist Michael Taylor[187] noted, "Science is not always right – very far from it. What marks it out from other fields of human endeavor is that, because of its formalized humility, it's always ready to correct itself when it makes a mistake. Scientists may not be humble people, but doing science forces us to act humbly."

To refute a false claim is for the benefit of all. To reject the practice of repeating the false claim, and to name those who keep repeating claims that are known to be untrue, is not defamation of such authors. On the contrary, it is a service to all who use science, which include the authors of erroneous claims. This is why authors and journals publish errata and retractions. The relentless pursuit of the truth is in the public interest.

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

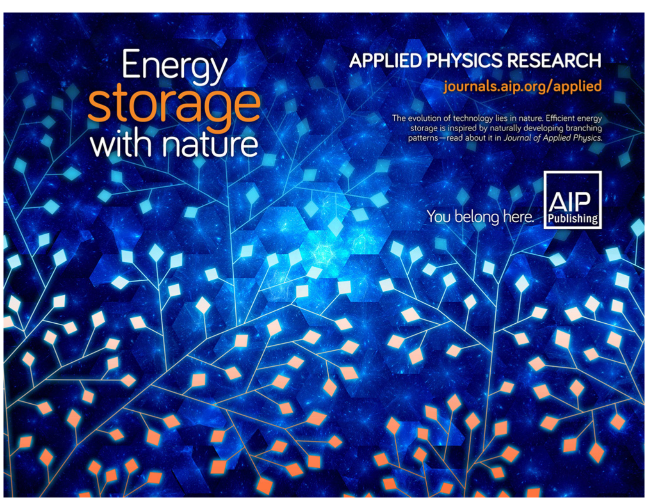


FIG. 11. The evolution of latent heat storage toward flow architectures that resemble design in nature. Poster at the AIP 2016 meeting made for illustrating the nature of evolution in physics.[184,185] Courtesy of Dr. Benedetta Camarota, AIP Publishing.

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