SCIENTIFIC REPORTS

OPEN

SUBJECT AREAS:
APPLIED PHYSICS
EVOLUTIONARY THEORY
MECHANICAL ENGINEERING
BIOENERGETICS

Received
9 December 2013

Accepted
22 January 2014

Published
10 February 2014

Correspondence and requests for materials should be addressed to A.B. (abejan@duke.edu)

Maxwell's Demons Everywhere: Evolving Design as the Arrow of Time

Adrian Bejan

Duke University Durham, North Carolina 27708-0300, USA.

Science holds that the arrow of time in nature is imprinted on one-way (irreversible) phenomena, and is accounted for by the second law of thermodynamics. Here I show that the arrow of time is painted much more visibly on another self-standing phenomenon: the occurrence and change (evolution in time) of flow organization throughout nature, animate and inanimate. This other time arrow has been present in science but not recognized as such since the birth of thermodynamics. It is Maxwell's demon. Translated in macroscopic terms, this is the physics of the phenomenon of design, which is the universal natural tendency of flow systems to evolve into configurations that provide progressively greater access over time, and is summarized as the constructal law of design and evolution in nature. Knowledge is the ability to effect design changes that facilitate human flows on the landscape. Knowledge too flows.

Well known is the arrow of time of the phenomenon of irreversibility. Heat flows from high to low temperature, not the other way around. Like water under the bridge, or over the dam. This natural tendency is expressed by the second law of thermodynamics. We see it in Fig. 1a, where the system is defined by the solid line, and the heat flow Q_H proceeds from high temperature T_H to low temperature T_L.

Less known is the time arrow of the phenomenon of evolution, which means design change[1,2]. Here I draw attention to its earliest articulation in thermodynamics, which was Maxwell's demon (for a review, see[3]). Maxwell argued that even though the temperature is uniform in an isolated system, the molecule speeds are not. He wrote: "Now let us suppose that such a vessel is divided into two portions, A and B, by a division in which there is a small hole, and that a being, who can see the individual molecules, opens and closes this hole, so as to allow only the swifter molecules to pass from A to B and only the slower molecules to pass from B to A. *He will thus, without expenditure of work*, raise the temperature of B and lower that of A (as shown in Fig. 2b)."

Results

In this paper I describe the demon in macroscopic terms. Imagine "a being" that can follow the flow of heat and divert some of it to flow through a contrivance—a design, or machine—that produces power, mechanical or electrical, Fig. 1b. This happens everywhere in nature, from the whole earth as a heat engine, to every animal as a vehicle with its own motor, Fig. 1c.

Start with Fig. 2a. The box is filled with a gas of uniform temperature T_1 and pressure P_1. The gas is moving in the box, with the kinetic energy KE_1 (state 1). Next, partition the box into A and B. The partition is highly conductive to the flow of heat. In one spot on the partition, the designer installed a sensitive instrument that measures the pressure on the two surfaces of the partition. Such a design can be built, operated, recorded, and described.

Time varying pressure differences occur across the partition, at every point, because when jets and eddies hit the wall the fluid stagnates and experiences a pressure rise (the stagnation pressure). The instrument monitors the pressures on the A and B sides of the partition. Whenever the B side is at a higher pressure than the A side, the instrument opens an orifice through which B fluid flows into the A chamber. This process continues until all the motion stops. In that final state the isolated system is isothermal, and the mass and pressure in A are greater than in B.

The thermodynamic analysis is detailed in the Supplement. In brief, the system consists of A and B, and is isolated. State 1 is the initial state of uniform temperature T_1, pressure P_1, and mass m. The reference state is (T_0, P_0), and KE_1 is the kinetic energy of all the fluid in motion at state 1. State 2d is a constrained equilibrium state. The temperature is uniform (T_2), the partition is closed, and the pressure on the A side ($P_2 + \Delta P$) is greater than on the B side ($P_2 - \Delta P$). The mass inventories of A and B are ($m/2 + \Delta m$) and ($m/2 - \Delta m$), respectively. The equilibrium pressure P_2 is in state 2 without partition. From $PV = mRT$ for state 2 with and without partition, we

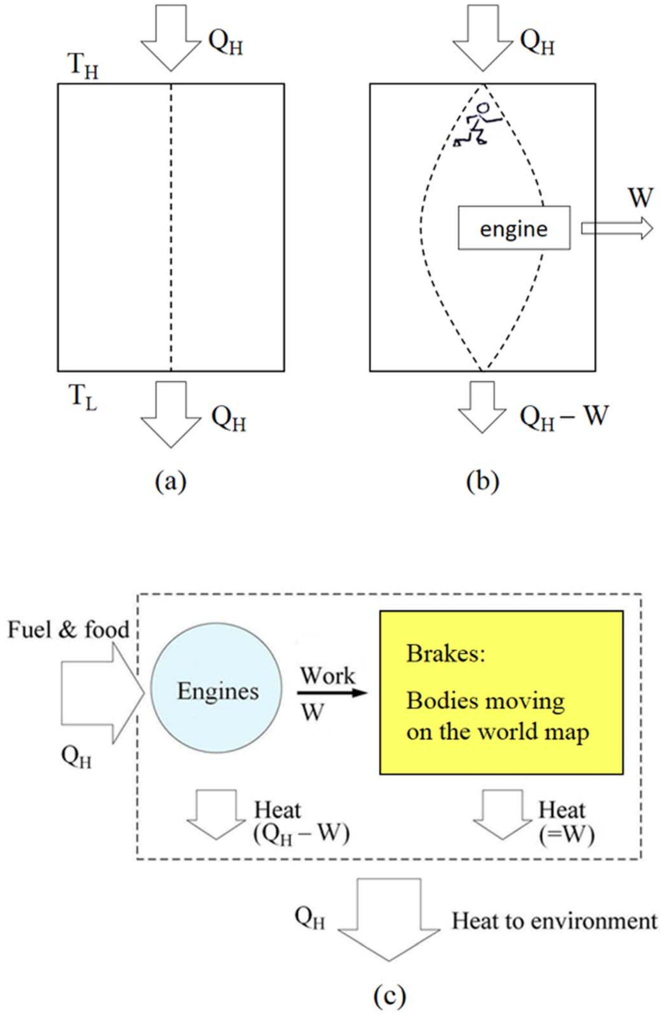

Figure 1 | **Closed system in steady state, with heat flow in and out.** (a) Without flow organization (design); (b) With flow organization; (c) Every moving body, animate or inanimate, functions as an engine that dissipates its power entirely into a brake during movement. The natural tendency of evolving design is the same as the tendency toward more power (the engine design, animal or machine), and toward more dissipation (mixing the moved with the ambient). (Figure drawn by Adrian Bejan).

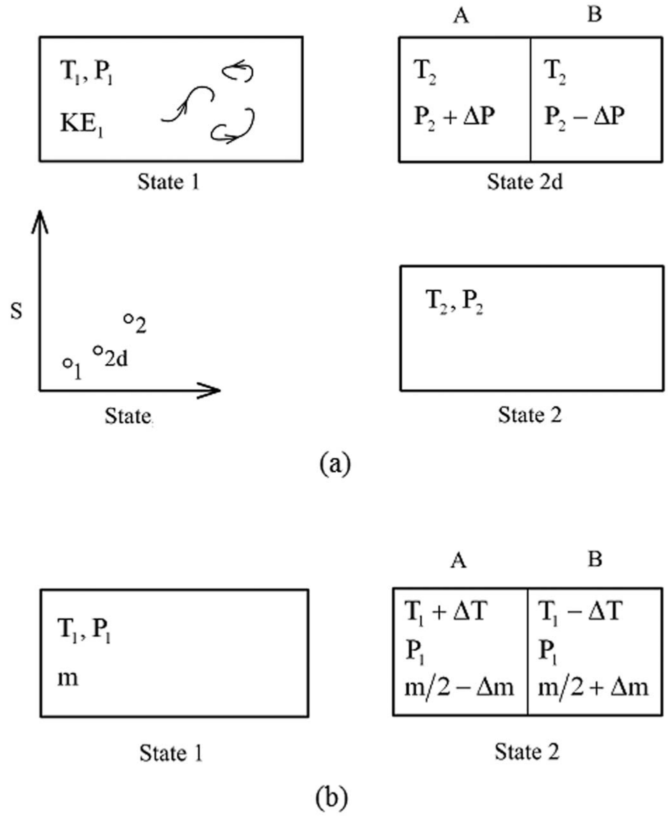

Figure 2 | (a) Isolated system containing an ideal gas in motion (state 1). If equipped with a designed partition, the system achieves a pressure difference across the partition (state 2d). If the designed partition is absent, then the system reaches a state of uniform pressure and temperature (state 2). (b) Maxwell's isolated system (state 1), and the state of nonuniform temperature established after the operation of a designed partition (state 2). (Figure drawn by Adrian Bejan).

find $\Delta P/P_2 = 2\Delta m/m$. From $PV = mRT$ for state 1 and state 2 (without partition) we find $P_2 = T_2P_1/T_1$. The system is isolated, therefore its energy remains constant, regardless of whether the partition is present in state 2. The entropy inventories at states 1, 2 and 2d are derived in the Supplement: S_1, S_{2d} and S_2.

In particular, when $\Delta P/P_2 \ll 1$ the entropy change from state 1 to state 2d (with partition) is $S_{2d} - S_1 = mc_v \ln(T_2/T_1) - mR(\Delta P/P_2)$. The second law requires $S_{2d} - S_1 \geq 0$, and this means that the excess pressure (ΔP) that can be expected on the A side cannot exceed a value dictated by the initial kinetic energy present in the gas system, namely $\Delta P/P_1 \leq KE_1/(mRT_1)$ when $T_2 - T_1 \ll T_1$ and $\Delta P \ll P_2$. If after state 2d the partition is removed, the system reaches state 2 without partition (E_2, S_2). The entropy change from sate 2d to state 2 is $S_2 - S_{2d} = mR(\Delta P/P_2) > 0$.

The second law is obeyed by all the processes possible in this macroscopic version of Maxwell's demon, namely processes 1 → 2d, 2d → 2, and 1 – 2. The difference between the two scenarios is one of scale. In Maxwell's microscopic view, the designer and the instruments are so small and accurate that they can detect velocity differences between individual molecules. In the macroscopic scenario presented in this paper, the designer and the instruments are at a much larger, visible and palpable scale.

Key is the system feature that unites the two scenarios. The partition that opens and closes in accord with measurements of differences between the A and B sides represents *design*, or *organization*—a flow configuration with a purpose, or a function. The system without partition does not have design. The macroscopic scenario makes the design evident, much more visible than Maxwell's microscopic argument.

Design can be measured, and its value is a characteristic of the system that possesses design. It is the ability of the system to generate useful energy (work, exergy, available work[4]). The value of the design in Fig. 2a is estimated by comparing state 2d with state 2. The system has the potential to produce work (useful energy, exergy) if placed in communication with one temperature reservoir, T_2. This quantity is the exergy (available energy) at state 2d relative to state 2, namely $\Xi = (U - T_2S)_{2d} - (U - T_2S)_2$, where $U_{2d} = U_2$, as dictated by the first law, and (T_2, P_2) is the reference state, therefore (cf. Supplement) in the limit $\Delta P/P_2 \ll 1$,

$$\Xi = mRT_2 \left(\frac{\Delta P}{P_2}\right)^2 \quad (1)$$

The physical value of the design increases rapidly with the design's ability to achieve a pressure difference across the diathermal partition at the end of the process 1 → 2d. In the work producing process contemplated in the analysis that leads to Eq. (1), the useful energy produced Ξ is dissipated in a brake, and the generated heat is absorbed by the system itself, which is at T_2.

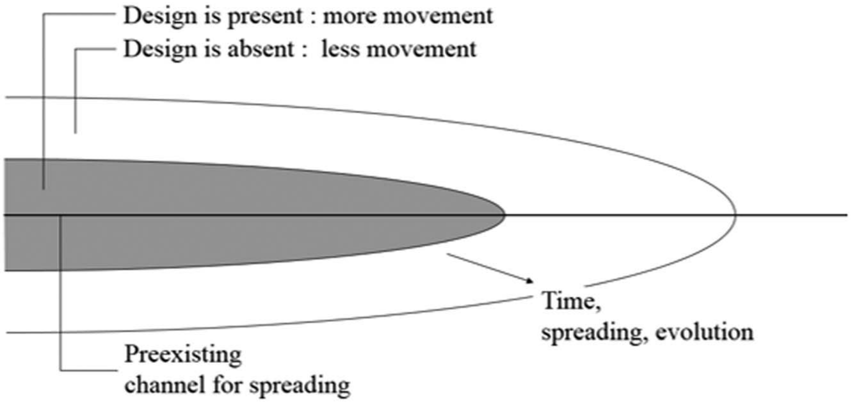

Figure 3 | Knowledge is the spreading of the ability to effect design changes that facilitate greater and more lasting movement over the covered territory. (Figure drawn by Adrian Bejan).

Interesting is that the physical value of this design, Eq. (1), is analogous to the physical value of Maxwell's design, Fig. 2b, where the system (m) is initially in state 1, at temperature T_1 and pressure P_1. At state 2, Maxwell's system has design: two chambers, A and B, at different temperatures, $T_1 + \Delta T$ and $T_1 - \Delta T$, separated by an adiabatic partition with an orifice opened and closed *with purpose*. The design value is the exergy at state 2 relative to the reference (dead) state (T_1, P_1), namely $\Xi = (U - T_1 S)_2 - (U - T_1 S)_1$, and (cf. Supplement)

$$\Xi = mc_P T_1 \left(\frac{\Delta T_1}{T_1}\right)^2 \quad (2)$$

This is analogous to Eq. (1). The value of Maxwell's design increases rapidly with its ability to build the temperature difference $2\Delta T$ across the adiabatic partition by opening and closing the "smart" orifice.

Discussion

Return to Fig. 1, which shows the more general (not isolated) system that underpins this entire mental viewing. With design, the system generates power (W), or exergy per unit time. With design, the system of Fig. 1b generates less entropy, as the generated entropy [namely, $(Q_H - W)/T_L - Q_H/T_H$] is less than in Fig. 1a (namely, $Q_H/T_L - Q_H/T_H$). Less entropy out makes it appear that more of the inflowing entropy (Q_H/T_H) is kept inside the system.

The evolution of design (organization) is a universal tendency of flow systems in nature, and it happens throughout animate and geophysical systems in accord with the constructal law[1,2]. In Fig. 1, this means that the time arrow points from (a) to (b), or to (c). This tendency is also recognized as self-organization, self-optimization, increasing complexity, order, networks, and scaling. It is also the basis for many disconnected (ad-hoc) contradictory statements of optimality (for reviews see Refs. 1,5,6) such as maximum entropy production, minimum entropy production, maximum flow resistance, minimum flow resistance, animal body mass scaling, uniform distribution of stresses in loaded solid structures, maximum growth rate of disturbances in turbulence, rapid solidification as dendritic design, and technology evolution (miniaturization, high density of functionality and minimum weight). All these ad-hoc statements are covered by the constructal law[1].

These phenomena represent one phenomenon, which is the time arrow of design change. Consider what happens to the produced power (W), which is the physical measure of the design. The power is destroyed in the process of moving mass horizontally on the world map, on land, on water and in the air (Fig. 1c). Everything that flows and moves does so because it is being pushed. The push comes from the power generated because of design. The dissipation resides in the environment that is displaced (penetrated) by the moving mass.

The physical effect of evolving design is more movement and greater access for all movers. This is what the "demons" achieve. This is the complete design of all animate or inanimate flow systems, from water flowing in river basins, to animal locomotion and urban traffic, and atmospheric and oceanic circulation[1,5-21].

Conclusion

New configurations and rhythms emerge so that they offer greater access to what flows—greater access to the available space, areas and volumes, and persistence in time. As a special class of evolving designs, humanity today is kept moving (with "sustainability") by the power produced in animal design and engines. The designs morph along with us, and our movement is facilitated over time.

The spreading of design change on the human landscape is known as better science, cognition, knowledge, security, automobile technology, healthcare and many more. Knowledge means flow design change that is useful, and the ability to make it happen.

Knowledge spreads on a territory naturally (Fig. 3). The boundary between those who know more and those who know less is advancing in time. The high is penetrating the low. In the high are the knowledgeable who move more than those in the low.

Maxwell's "demons" are happening naturally, and their physical effect is more movement on earth over time, animate and inanimate alike.

1. Bejan, A. & Lorente, S. The constructal law and the evolution of design in nature. *Phys Life Rev* **8**, 209–240 (2011).
2. Basak, T. The law of life: The bridge between Physics and Biology. *Phys Life Rev* **8**, 249–252 (2011).
3. Leff, H. S. & Rex, A. F. *Maxwell's Demon 2: Entropy, Classical and Quantum Information, Computing* (CRC Press, Boca Raton, FL, 2002).
4. Bejan, A. *Advanced Engineering Thermodynamics*, 3rd ed. (Wiley, Hoboken, 2006).
5. Reis, A. H. Constructal theory: from engineering to physics, and how flow systems develop shape and structure. *Appl Mech Rev* **59**, 269–282 (2006).
6. Bejan, A. & Lorente, S. Constructal law of design and evolution: Physics, biology, technology, and society. *J Appl Phys* **113**, 151301 (2013).
7. Chen, L. Progress in study on constructal theory and its applications. *Science China Tecn Sci* **55**, 802–820 (2012).
8. Kalason, P. *Le Grimoire des Rois: Théorie Constructale du Changement* (L'Harmattan, Paris, 2007).
9. Miguel, A. F. Natural flow systems: acquiring their constructal morphology. *Int J Design & Nature Ecodyn* **5**, 230–241 (2010).
10. Quéré, S. Constructal theory of plate tectonics. *Int J Design & Nature Ecodyn* **5**, 242–253 (2010).
11. Reis, A. H. Constructal view of scaling laws of river basins. *Geomorphology* **78**, 201–206 (2006).
12. Rocha, L. *Convection in Channels and Porous Media. Analysis, Optimization, and Constructal Design* (VDM Verlag, Saarbrücken, 2009).
13. Lorenzini, G., Moretti, S. & Conti, A. *Fin Shape Optimization Using Bejan's Constructal Theory* (Morgan & Claypool Publishers, San Francisco, 2011).
14. Bachta, A., Dhombres, J. & Kremer-Marietti, A. *Trois Ètudes sur la Loi Constructale d'Adrian Bejan* (L'Harmattan, Paris, 2008).

15. Miguel, A. F. Dendritic structures for fluid flow: Laminar, turbulent and constructal design. *J Fluids Structures* **26**, 330–335 (2010).
16. Kasimova, R. G., Obnosov, Yu V., Baksht, F. B. & Kacimov, A. R. Optimal shape of anthill dome: Bejan's constructal law revisited. *Ecological Modelling* **250**, 384–390 (2013).
17. Tuhtan, J. A. Go with the flow: connecting energy demand, hydropower, and fish using constructal theory. *Phys Life Rev* **8**, 253–254 (2011).
18. Gosselin, L. Optimization of tree-shaped fluid networks with size limitations. *Int J Therm Sci* **46**, 434–443 (2007).
19. Tondeur, D. D., Fan, Y. & Luo, L. Constructal optimization of arborescent structures with flow singularities. *Chem Eng Sci* **64**, 3968–3982 (2009).
20. Reis, A. H. & Gama, C. Sand size versus beachface slope – an explanation based on the Constructal Law. *Geomorphology* **114**, 276–283 (2010).
21. Ventikos, Y. The importance of the constructal framework in understanding and eventually replicating structure in tissue. *Phys Life Rev* **8**, 241–242 (2011).

Acknowledgments

This research was supported by grants from the National Science Foundation and the National Renewable Energy Laboratory.

Author contributions

As the sole author, Prof. Bejan has contributed 100% to this manuscript.

Additional information

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

Competing financial interests: The author(s) declare no competing financial interests.

How to cite this article: Bejan, A. Maxwell's Demons Everywhere: Evolving Design as the Arrow of Time. *Sci. Rep.* **4**, 4017; DOI:10.1038/srep04017 (2014).