

Review Article

Entropy Growth Is the Manifestation of Spontaneity

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Every student of thermodynamics grasps entropy growth in terms of dissipation of energy. The real nature of energy and entropy is subtle. This critical review of the evolution of thermodynamic thought uncovers the remarkable advance on our understanding of energy made by Kelvin with his dissipation of energy proposition. Maxwell and Planck, however, pointed out that dissipation of energy does not exhaust growth of entropy (i.e., the idea of spontaneity), and in fact, as it is shown here, Kelvin's proposition of dissipation of energy (1852) is subsumed under the principle of the increase of entropy (Clausius, 1865). It is necessary, therefore, for thermodynamics to become a coherent conceptual system, to introduce spontaneity as an *independent* concept. Instead of the heat-work dyad framework, the introduction of spontaneity entails energy transformation to be viewed in terms of a triad framework of heat (from the reservoir)-work-spontaneity. Spontaneity is the new energy in the triad framework, and it is also clear that energy commodity (fungible energy or energy carriers) is only one kind of spontaneity, *stock spontaneity*; the other kind is *ongoing spontaneity*, the consideration of which is necessary for comprehending problems of homeostasis in both the organic and inorganic worlds.

1. Introduction

William Thomson (later Lord Kelvin) established energy, alongside force, as a central concept in physics as well as everyday life by his formulation of the principle of dissipation of energy [1]. This principle has been identified with the principle of the increase of entropy formulated by Clausius [2, 3]. However, how the two principles are used suggests otherwise. The Kelvin treatment has evolved into the related concept of exergy¹ (see Note 1 and [4] for definition of exergy) or maximum useful work. And the Clausius treatment has been developed by Gibbs into the Clausius-Gibbsian equilibrium thermodynamics. Whereas the Kelvinian ideas of energy and exergy dissipation are extremely useful, the Clausius concepts of entropy and entropy production are in fact the basic ones: “dissipation of mechanical energy” [1, pp. 511–514] is only one example of tendencies in entropy production or spontaneity,² albeit the most important one as Kelvin defined it (see below); even so, a whole perspective is possible only if thermodynamics is understood in terms of both energy dissipation and entropy growth—the former spontaneous and the latter universal. Here we show that

the concept of maximum useful work is subsumed under the entropy law and, thereby, thermodynamics becomes a coherent conceptual system in which an *independent* concept of spontaneity plays a central role. The unification makes it clear that energy commodity (fungible energy or energy carriers) is only one kind of spontaneity, *stock spontaneity*; the other kind is *ongoing spontaneity*, the consideration of which is necessary for comprehending problems of homeostasis in both the organic and inorganic worlds.

2. Kelvin's Treatment and Clausius' Treatment: Dissipation and Entropy

Thomson and Clausius shared the credit for the theoretical structure that the science of thermodynamics took in the 19th century and has since evolved into the present forms—largely, as the result of their success in resolving (reconciling) the conflict between the *mechanical equivalent of heat* and *Carnot's Principle*. The resolution and the corresponding form of the structure, however, took different shapes.

Thomson first realized that the acceptance of the interconvertibility of heat and work did not have to discard

Carnot's Principle, a corollary of which is *Carnot's function*, $\mu(t)$, a function of temperature. His resolution led to the expression, obtained in 1851 [5, pp. 189-190],

$$W_{\text{rev}} = Q_1 \left[1 - \exp \left(- \int_{t_2}^{t_1} \mu(t) dt \right) \right], \quad (1)$$

where t_1 is specific temperature of the hot body and Q_1 its heat rejection and t_2 the temperature of the cold body or the heat sink. In 1854 he returned to his 1848 idea—the idea that μ (instead of being a function of temperature) *determines* an absolute temperature scale, T ,

$$\mu = \frac{1}{T}, \quad (2)$$

substitution of which into (1) yielded the celebrated formula, the Carnot-Kelvin formula [6, pp. 393–395],

$$W_{\text{rev}} = Q_1 \left(1 - \frac{T_2}{T_1} \right). \quad (3)$$

Equation (2) and the introduction of the absolute temperature, (3), [7], and Proposition of dissipation of mechanical energy [1] summarize Thomson's three contributions on thermodynamics: engineering application of thermodynamics is largely based on the Carnot-Kelvin formula and the later introduction of the concept of *exergy*, which was derived from the Proposition.

In another 1854 paper [8, pp. 236-237], Thomson obtained, for a reversible cyclic process of a system which can exchange heat with an arbitrary number of heat reservoirs, the result

$$\sum_i \frac{Q_i}{T_i} = 0. \quad (4)$$

Clausius [9] too introduced a similar idea that $\oint (dQ/T)$ should be zero for a reversible cycle and considered the nonzero nature of the integral for an irreversible cycle as an inequality. In a second paper [10], Clausius obtained the form of the inequality that is known today as Clausius' Inequality: for real processes, $\oint (dQ/T)$ is subject to

$$\oint \frac{dQ}{T} \leq 0, \quad (5)$$

where the equality applies only for reversible processes. This finally led in 1865 [2, 3] to the introduction of entropy, $dS = (\delta Q/T)_{\text{rev}}$, and the principle of the increase of entropy for isolated systems (changing spontaneously from A to B),

$$S_B \geq S_A. \quad (6)$$

The 1865 paper closed with the statement, “*the entropy of the universe strives to attain a maximum value*”; with this phrasing, Gibbs began his 1875 paper [11], which introduced the theory of equilibrium. This is essentially what is known today as the classical thermodynamics.

3. Dissipation of Energy and Exergy

The growth of entropy and the dissipation of energy are two perspectives at the core of thermodynamics. “Entropy and the dissipation of energy are as inseparable as Siamese twins in the thought of every student of thermodynamics” noted Daub [12]. Though inseparable, their applications in engineering and in science diverge in subtle but important ways.

Every student of thermodynamics grasps entropy growth in terms of dissipation of energy. Every time when an engineer applies energy balance via the first law of thermodynamics that includes the consideration of loss in mechanical energy resulting from its dissipation into heat or enthalpy loss, she/he is in fact simultaneously applies the second law, one example of which can be found in explaining why irreversibility in combustion process in an internal combustion engine leads to reduction in mechanical power output. Entropy increase resulting from combustion leads to higher enthalpy loss in exhaust gas. On surface, the account of energy balance among fuel-air enthalpy (fixed), exhaust enthalpy (if that is higher), and work output (then which will be lower) explains the loss in power, while the real underlying reason is the combustion entropy growth which causes the necessary higher enthalpy loss and thereby lower power output.

The idea of energy being characterized in terms of its conservation *and* its availability came from Kelvin. He faced the conflict between the idea that the production of work requires the *transfer* of heat (Carnot's Principle) and the competing idea that it requires the *consumption* of heat (the mechanical equivalent of heat). Kelvin developed his solution resolving this conflict by making direct connection of the direction of changes to his conception of lost energy, or “dissipation of energy,” as given in the passage in the draft of his 1851 paper [5],

The difficulty which weighed principally with me in not accepting the theory so ably supported by Mr. Joule was that the mechanical effect stated in Carnot's Theory to be *absolutely lost* by conduction is not accounted for in the dynamical theory otherwise than by asserting that *it is not lost*; and it is not known that it is available to mankind. The fact is that it may, I believe, be demonstrated that the work is *lost to man* irrecoverably but not lost in the material world. Although no destruction of energy can take place in the material world without an act of power possessed only by the supreme ruler, transformations take place which removes irrecoverably from the control of man sources of power which, if the opportunity of turning them to his own account had been made use of, might have been rendered available.³

Kelvin, in this remarkable passage, made the fundamental distinction between destruction of energy and lost energy (energy lost to man or, the term he later introduced, dissipation of energy). By the latter he really meant the dissipation of energy or power available to mankind: he connected “irrecoverable” direction of changes, though involving no destruction

of energy, to loss in available energy. Our understanding on energy at this point (1852–54) may be summarized as

Whereas Joule demonstrated non-destruction (i.e., conservation) of energy in all energy transformations, Kelvin posited that in such thermodynamic changes, nonetheless, the usefulness of energy to mankind is predisposed to be lost and would be lost if man does not turn them to his own account.

While he made the distinction between destruction of energy and loss of available energy, he at the same time conflated the *transfer* of heat and the *consumption* of heat into the assertion that the production of work depends solely on the transformation and consumption of high grade energy or high grade heat. That is, according to (3) we have the dyad framework of heat and work or

$$\text{Heat}(Q_1) \iff \text{Work}(W_{\text{rev}} [\geq W]). \quad (7)$$

These kinds of consideration under the dyad framework have been formalized into the theory of exergy: energy can be neither destroyed nor created, since energy (of all forms) is conserved: only one energy *form* (e.g., mechanical energy [1]) can be destroyed converting into another *form* of equal amount of energy. Energy of the same amount but of different forms can have different fractions of the amount that are “available to mankind.” Engineers thus deal with the dissipation of exergy, that is, maximum useful work—which is defined as the maximum fraction of an energy form which can be transformed into work ([4], see also Note 1). In other words, exergy is the valuable part of energy which can be converted into useful work, and the remaining part is called *anergy*. For example, in the case of Q_1 , the valuable part of it is $Q_1(1 - T_2/T_1)$ and anergy is $Q_1(T_2/T_1)$. Even though a less restrictive definition of exergy exists [13], the above definition is the one by which every engineering student of thermodynamics understands “what is exergy?” With this understanding, exergy can only dissipate: the growth or increase of exergy is impossible. This is a misunderstanding made possible because Kelvinian treatment has not been integrated completely with the entropy growth approach.

With his incomparable intellect and historical contribution (evidenced by the unit of absolute temperature, *kelvin*, named after him and the fact that he was the key scientist credited to ushering in “the epoch of energy” by his biographers Smith and Wise [14]), Thomson did not provide a logical formulation of the principle of dissipation of energy in the 1852 paper [1] as the second law of thermodynamics; instead, he simply declared the three “general conclusions”⁴ at the end of the short paper. It is striking in the manner Kelvin presented his principle: Von Baeyer commented on it with these words, “The vague, metaphysical character of the principle of dissipation of energy [see General Conclusions #2 and #3 in Note 4]—the “natural tendency” of energy toward dilution—contrasts curiously with the robust, tangible way in which Thomson described the world [in his other scientific writings]” [15]. Uffink characterized it simply as “the unargued statements of Kelvin” [16].

“Clausius was the first to show the relationship between lost work and irreversible entropy increase. . . [then] the first

explicit and legitimate merge of entropy and dissipation [took place] in Maxwell’s final revised version of his classic work on heat,” wrote Daub in a historical study [12]. After the derivation of *available energy* for systems in interaction with their surroundings, Maxwell turned his discussion to isolated composite systems [17]:

If the system. . . from which neither matter nor heat can escape, then the amount of energy converted into work will be greatest when the system is reduced to thermal and mechanical equilibrium. . . (page 189)

. . . there takes place a communication of a quantity $H[Q]$ of heat from a body at temperature θ_1 to a body at temperature θ_2 , the increase of the total entropy of the system arising from the communication is,

$$H \left(\frac{1}{\theta_2} - \frac{1}{\theta_1} \right) \dots \text{(page 191)}. \quad (8)$$

Maxwell then arrived at the conclusion,

. . . the available energy is therefore diminished by this quantity [the product of the entropy increase and Θ (the final equilibrium temperature of the system)]. . . Processes of this kind, by which, while the total energy remains the same, the available energy is diminished [for the reason of corresponding increase in the total entropy], are instances of what Sir W. Thomson has called the Dissipation of Energy. (page 192)

If we disregard two unnecessary limitations that marred the generality of Maxwell’s treatment (H is assumed to be small and the specific use of the final temperature, both will be removed below), this is a clear account that energy is not always necessarily reduced (“dissipated” in terms of how Kelvin used it) for lost opportunity in useful work production: “while the total energy remains the same, the available energy is diminished.” Realizing that a fundamental difference exists in this discourse from the universal dissipation of energy, Maxwell added, “The doctrine of the dissipation of energy is closely connected with that of the growth of entropy, but is by no means identical with it.”

This same point is made somewhat differently by Planck,

The real meaning of the second law has frequently been looked for in a “dissipation of energy.” This view, proceeding, as it does, from the irreversible phenomena of conduction and radiation of heat, presents only one side of the question. There are irreversible processes in which the final and initial states show exactly the same form of energy, for example, the diffusion of two perfect gases (Section 238), or further dilution of a dilute solution. Such processes are accompanied by no perceptible transference of heat, nor by external work, nor by any noticeable

transformation of energy. They occur only for the reason that they lead to an appreciable increase of the entropy [18, pp. 103-104].

Even though Planck here did not talk about useful work or available energy directly, he was clear that dissipation of energy as representing spontaneous changes does not *exhaust* growth of entropy, which does happen in every change. Our understanding on thermodynamic changes at this point (the publication of *Treatise* [18]) as derived from Clausius-Maxwell-Planck (CMP) may be summarized as

Kelvin had made the case that, in all thermodynamic changes, the availability of energy is lost as a result of changes in the form of the source energy. Clausius, Maxwell and Planck demonstrated, however, that the availability can also be lost even if there is NO change in the form of energy of some source system so long as there is increase of the total entropy of the universe.

4. The Subsumption of the Dissipation of Energy under the Entropy Principle

When one combines the points made by Maxwell (about energy, available energy (maximum useful work), and entropy growth) and Planck (direction of thermodynamic changes, energy dissipation, and entropy growth), it amounts to the claim that availability or available energy has more to do with entropy than energy. It is worthwhile to place the CMP argument on more rigorous ground so that an understanding of the entropy principle's role in the theory of available work (reversible work) can be obtained.

A more rigorous demonstration is possible today because of a new corollary of the second law, *entropic drive principle* [13], which is used here: consider events of a system in interaction with a T_0 reservoir undergoing change from A to B . The system and reservoir pair can change from the same A to B in infinitely different events ranging from spontaneous event to reversible event. The corollary is made of the following two results. (1) The maximum useful work in a reversible event is given as

$$W_{\text{rev}} = T_0 (\Delta_p S)_{\text{universe}}, \quad (9)$$

where $(\Delta_p S)_{\text{universe}}$ is the total entropy production of the system and the reservoir ("universe") in a spontaneous event. And (2) the range of possible arbitrary events—with one of the possible events represented in terms of Q amount of heat the system receives from the reservoir—is defined by the Poincare range [19],

$$Q_{\text{spon}} \leq Q < Q_{\text{rev}}. \quad (10)$$

Note also that

$$T_0 (\Delta_p S)_{\text{universe}} = Q_{\text{rev}} - Q_{\text{spon}} = T_0 \Delta S - Q_{\text{spon}}, \quad (11)$$

where ΔS is the system entropy gain.

Suffice it to state that (9) together with (11) reduces to all known specific maximum useful work results, including (3)

resulting from $(\Delta_p S)_{\text{universe}} = (-Q_1/T_1) + (Q_1/T_2)$ and $T_0 = T_2$, thus

$$T_0 (\Delta_p S)_{\text{universe}} = T_2 \left(\frac{-Q_1}{T_1} + \frac{Q_1}{T_2} \right) = Q_1 \left(1 - \frac{T_2}{T_1} \right) \quad (12)$$

—and the Gibbs free energy resulting from $-Q_{\text{spon}} = H_{\text{reactant}} - H_{\text{product}}$, thus

$$\begin{aligned} T_0 \Delta S - Q_{\text{spon}} &= T (S_{\text{prod}} - S_{\text{react}}) + (H_{\text{reactant}} - H_{\text{product}}) \\ &= (H - TS)_{\text{react}} - (H - TS)_{\text{prod}}. \end{aligned} \quad (13)$$

Now Consider Isolated Systems. Entropy production in these cases is by definition

$$(\Delta_p S)_{\text{universe}} = \Delta S. \quad (14)$$

Is T_0 the final temperature as Maxwell indicated? It turns out that since the spontaneous event of an isolated system does not interact with a reservoir, T_0 in (9) can be the temperature of any reservoir, $T_{\text{reservoir}}$, with which a reversible event of the system interacts; that is, (9) becomes

$$W_{\text{rev}} = T_{\text{reservoir}} \Delta S. \quad (15)$$

Note that while $(\Delta_p S)_{\text{universe}}$ in (9) depends on T_0 , ΔS in (15) is independent of any reservoir temperature.⁵ Therefore, (15) is applicable for arbitrary temperature of an available reservoir (examples below). Its applicability is free of any restriction in temperature change as long as the isolated system returns to its natural final end state. The restriction Maxwell placed on his discussion, "the rise of the final temperature is small," is unnecessary.

The application of (15) is especially significant since it represents the latent potential of production of useful work from pure spontaneous systems of isolated kind. We consider below two examples with reservoirs of arbitrary temperatures to show the validity of (15).

It is well known that a free expansion composite system can be brought into thermal contact with a heat bath of the same system temperature T to absorb Q heat from the bath converting it 100% into useful work of amount $T \Delta S$ [13, 18–20]. A moment of reflection shows that if the temperature of the reservoir $T_{\text{Reservoir}}$ is different from the gas temperature T , reversible work will be given by the same expression $T_{\text{Res}} \Delta S$ (see Figure 1).

Consider a second example of isolated composite thermal system: blocks X and Y (X is aluminum ($c_{pX} = 0.900$ kJ/kg · K) with $m_X = 0.5$ kg, Y is copper ($c_{pY} = 0.386$ kJ/kg · K) with $m_Y = 1$ kg) initially at 100 and 500°C, respectively (state A), are brought together undergoing a *spontaneous* heat transfer process to a final state B of 557.84 K with corresponding entropy change 0.054949 kJ/K. Now consider a Carnot heat engine operating between X and Y producing work while the system undergoes a *reversible* isentropic change to a final temperature of 522.35 K with corresponding reversible work of 29.667 kJ. For the comparison of the two events, one needs

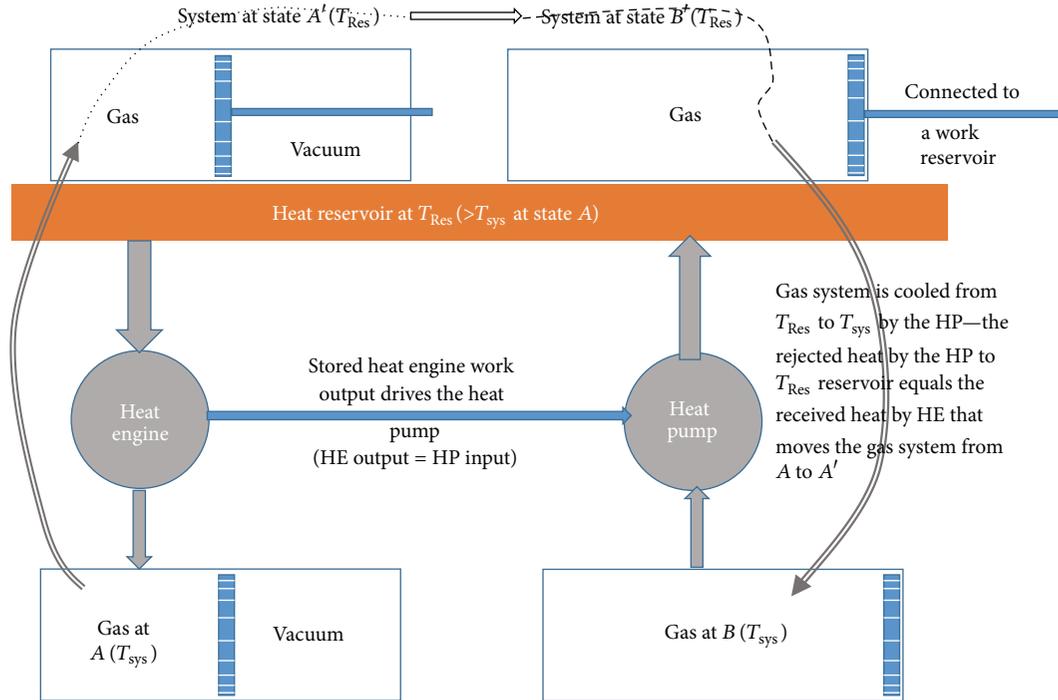


FIGURE 1: Schematic of a controlled “free expansion” of a gas from state A to state B, $A \rightarrow B$, with a heat reservoir of T_{Res} higher than system T_{Sys} . The facilitation of moving the system between T_{Sys} and T_{Res} then back involves no net work; thus, the overall process yields $T_{res} \Delta S = NRT_{res} \ln(V_B/V_A)$ work as given by (15).

TABLE 1

Reservoir T_{Res}	$T_{Res} \Delta S$	Heat engine work output	Heat pump work input	Net work output
522.35 K	28.703 kJ		-0.964 kJ	29.667 - 0.964 = 28.703 kJ
557.84 K	30.653 kJ	0.986 kJ		29.667 + 0.986 = 30.653 kJ
539.90 K*	29.667 kJ	0.2437 kJ →	-0.2437 kJ	29.667 kJ

*The third case involves the operation of, first, a heat engine followed by a heat pump.

to bring the system back from 522.35 K after the 1st isentropic step to B—calling it the *second step* of the reversible events. A moment of reflection shows three possible reversible event options (of infinite number of possibilities) associated with three heat reservoir temperatures (see Table 1 and Figure 2 for detailed comparative values of the three options).

Both Figure 2 and Table 1 provide quantitative details of supporting the validity of (15).

Kelvin connected the direction of thermodynamic (i.e., spontaneous) changes to the dissipation of energy or the idea of available work. By proclaiming the universal dissipation of energy, he mistook a spontaneous process of dissipation of energy to be a universal process of increase of entropy. This was rejected by Planck when he argued that dissipation of energy does not exhaust increase of entropy. In support of CMP argument, I have demonstrated in [13] and here that *all* opportunity in the production of useful work corresponds to increase in total entropy of universe in accordance with (9) and (15). That includes cases that involve no change in the energy form of source systems that both Maxwell and Planck identified and that the author introduced in [13] and

two examples of isolated systems discussed here in Figures 1 and 2. That is to say, the proposition of dissipation of energy is subsumed under the principle of the increase of entropy. The entropy principle provides the full determination through (9) and (15) of maximum useful work.

5. Spontaneity and the Triad Framework

The tendency to the dissipation of high grade energy is spontaneous, not universal; what is universal is increase in entropy [21]. The very universal entropic tendency in nature means that nature abounds in opportunity for constructive work and useful outcome through active management [13, 22] of this universal tendency. Dissipation of exergy is subsumed under the entropy principle. Dissipation of energy has served well (with appreciation to Kelvin) as a proxy to entropy growth, which is the real driving force of the universe. Had dissipation of energy exhausted growth of entropy, there would have been no need of an independent concept of spontaneity. The proxy would have been the real thing; but of course, it is not.

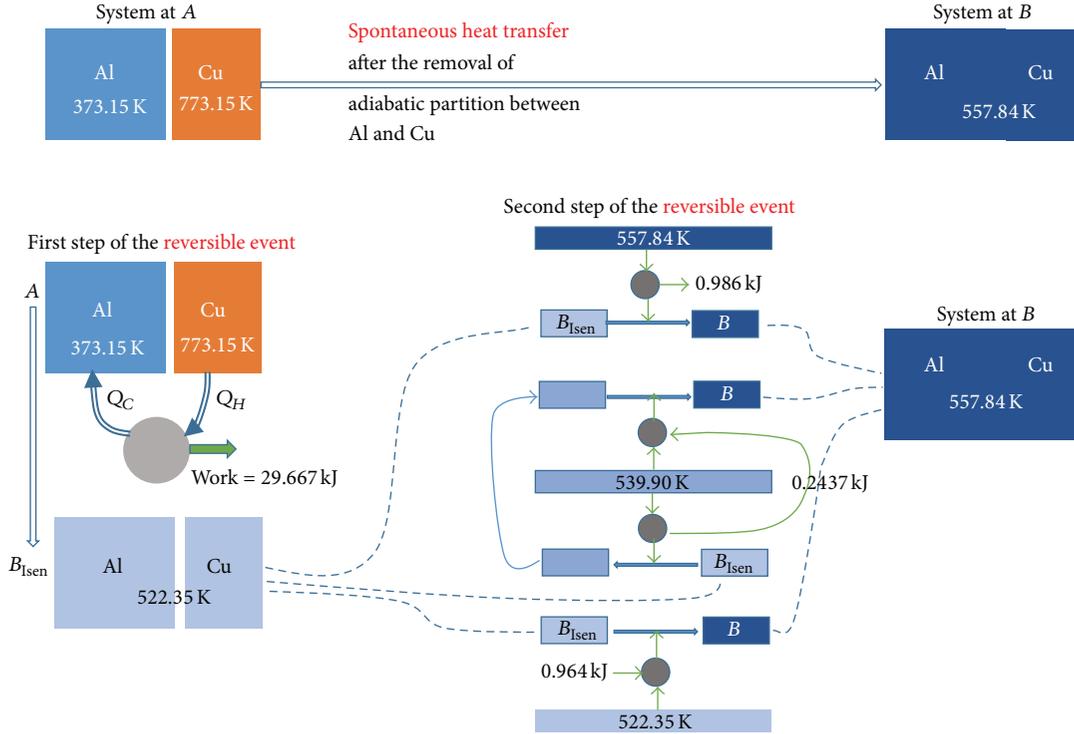


FIGURE 2: Schematic of the two events: the spontaneous event (shown in top) and the reversible event (in three options, shown in the lower part, of three different reservoir temperatures).

It is useful, therefore, to introduce an *independent* concept of spontaneity, which is a measure of the non-equilibriumness of a system from its internal equilibrium, defined for isolated systems as,

$$\text{Spontaneity} \equiv T_{\text{Res}} \Delta S \quad (16)$$

or, for general systems in their interaction with a heat reservoir of T_0 ,

$$\text{Spontaneity} \equiv T_0 (\Delta_p S)_{\text{universe}}, \quad (17)$$

where

$$(\Delta_p S)_{\text{universe}} = \text{function}(T_0). \quad (18)$$

Instead of the heat-work dyad framework,

$$\text{Heat}(Q_1) \iff \text{Work}(W_{\text{rev}} [\geq W]), \quad (19)$$

the introduction of spontaneity entails energy transformation to be viewed in terms of a triad framework of spontaneity-heat (from the reservoir)-work (Figure 3). In the case of a Carnot engine, the alternative triad representation to the above dyad relation is as follows:

$$\text{Spontaneity} \left(T_0 (\Delta_p S)_{\text{universe}} = T_2 \left(\frac{-Q_1}{T_1} + \frac{Q_1}{T_2} \right) \right)$$

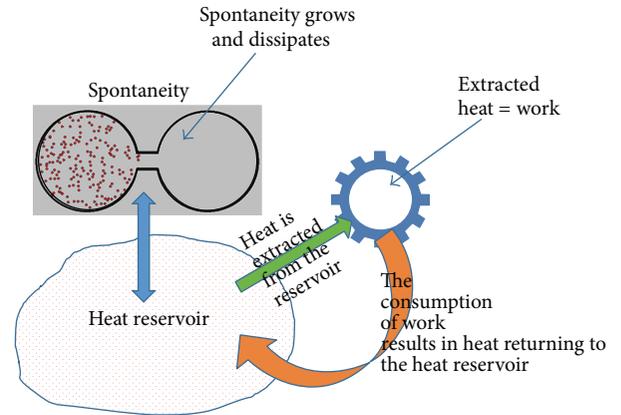


FIGURE 3: The triad framework of spontaneity, heat from heat reservoir, and useful work. Note 1: spontaneity is non-equilibriumness in nature, which comes from the accelerating expansion of the universe. Note 2: consumption of work resulting in heat, which returns to the surrounding heat reservoir.

$$\iff \text{Heat} \left(Q - Q_{\text{spon}} \leq Q_{\text{rev}} - Q_{\text{spon}} = -Q_1 \frac{T_2}{T_1} - [-Q_1] \right)$$

$$\iff \text{Work} \left(W \leq W_{\text{rev}} = Q_1 \left[1 - \frac{T_2}{T_1} \right] \right).$$

(20)

Spontaneity is the new energy [13, 21, 23] (Figure 3) in the triad framework. Common energy commodity (energy

carriers) is only one kind of spontaneity, *stock spontaneity*; the other kind is *ongoing spontaneity* [13, 21]. Moreover, spontaneity is being increased at the same time it dissipates. As Price noted, “. . .the puzzle is not about how the universe reaches a state of high entropy, but about how it comes to be starting from a low one.” [24]. One emerging answer to that question—instead of starting from a low one—is that universe’s entropy and non-equilibrium-ness are simultaneously increasing as a result of the accelerating expansion of the universe [25–29]: as Landsberg put the matter by entitling his paper, “Can entropy and order [i.e., non-equilibrium-ness] increase together?” [28] In fact, it is the creation of non-equilibrium-ness in universe that gives rise to the universal tendency of entropy growth or the dissipation of spontaneity in the first place. These perspectives are consistent with the following interpretation,

With the connection of available work to the concept of spontaneity, i.e., non-equilibrium-ness of the universe, and the realization of the possibility of simultaneous increase of entropy and non-equilibrium-ness of the universe, unlike energy and entropy, non-equilibrium-ness (room in entropy growth) as the driver of the universe is being continually renewed even as man turns it to his own beneficial account by taking advantage of the tendency of non-equilibrium-ness toward equilibrium.

6. Concluding Remarks

Spontaneity is the missing concept in the conventional conception of energy transformation. Without it, we have the incoherent view that energy (stock spontaneity) in itself is what matters without appreciation of the necessity of both spontaneity and heat reservoir—the latter either as T_0 – reservoir in (9) or as $T_{\text{reservoir}}$ – reservoir in (15). Instead of being passive heat sinks, the real significance of heat reservoirs is their participatory role in the production of work and power. The effect of reservoir temperature is more subtle than the general understanding as noted in Note 5. Spontaneity is the driver of the universe: we may rephrase what Carnot wrote, “heat alone is not sufficient to give birth to the impelling power: it is necessary that there should also be cold; without it, the heat would be useless,” [30] as heat alone is not sufficient to produce work or sustain homeostasis: it is necessary that there should also be *spontaneity*; without it, the heat would be useless. In certain sense, the concept of spontaneity and the triad framework can be found in Carnot’s 1824 magnum opus [30].

Finally, a new perspective on the non-equilibrium-ness of living objects and possibly man-made objects in terms of homeostasis in their existence is introduced in [21]: homeostatic systems have need of the surrounding environment and optimally use stock spontaneity (e.g., calories in food for nutritive needs) for managing ongoing spontaneity in the surrounding environment for meeting its other needs.

Definition of Terms

W_{rev} :	Maximum useful work or reversible useful work or available work, which, though synonymous with available energy, is a better term because without the word “energy” it does not imply W_{rev} to be necessarily derived from energy of the source system
T_0 :	Temperature of the reservoir with which a system is in interaction
T_{Res} :	Arbitrary temperature of an available reservoir, from which an isolated system can extract heat with its tendency toward equilibrium for the production of useful work
$(\Delta_p S)_{\text{univ}}$:	Total entropy increase of the universe (system + T_0 -surrounding reservoir) during a spontaneous event. Note: it depends on the temperature, T_0 , of the selected reservoir
ΔS :	Entropy increase of an isolated system. Note: it is independent of the temperature, T_{Res} , of an available reservoir
Q_{spont} :	Heat received by a system from the reservoir during a spontaneous event
Q_{rev} :	Heat received by a system from the reservoir during a reversible event
Q :	Heat received by a system from the reservoir during an arbitrary event within the Poincare range (see (10)).

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

Endnotes

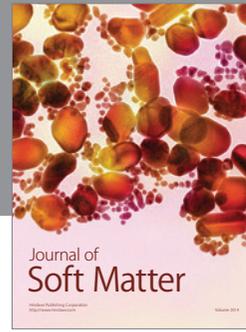
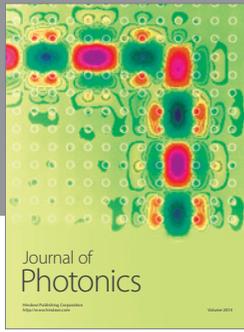
1. On page 298 of [4], the definition of *exergy* is given as “The maximum fraction of an energy form which (in a reversible process) can be transformed into work is called exergy. The remaining part is called anergy, and this corresponds to the waste heat.”
2. On pp. 103-104 of [18, Planck, (1969). *Treatise on Thermodynamics*, 3rd edition. (Dover)], Planck wrote, The real meaning of the second law has frequently been looked for in a “dissipation of energy.” This view, proceeding, as it does, from the irreversible phenomena of conduction and radiation of heat, presents only one side of the question. There are irreversible processes in which the final and initial states show exactly the same form of energy, for example, the diffusion of two perfect gases (Section 238), or further dilution of a dilute solution. Such processes are accompanied by no perceptible transference of heat, nor by external work, nor by any noticeable transformation of energy. They occur only for the reason that they lead to an appreciable increase of the entropy.

3. This passage is from a draft of [5]. It is taken from quotation in [14, page 329].
4. Reference [1] ends with the declaration of three “general conclusions”:
 - (1) “There is at present in the material world a universal tendency to the dissipation of mechanical energy.”
 - (2) “Any *restoration* of mechanical energy, without more than an equivalent of dissipation, is impossible in inanimate material processes, and is probably never effected by means of organized matter, either endowed with vegetable life or subjected to the will of an animated creature.”
 - (3) “Within a finite period of time past, the earth must have been, and within a finite period of time to come the earth must again be, unfit for the habitation of man as at present constituted, unless operations have been, or are to be performed, which are impossible under the laws to which the known operations going on at present in the material world are subject.”
5. Maximum useful work derived from isolate systems, therefore, decreases with decreasing reservoir temperature according to (15). But, because $(\Delta_p S)_{\text{universe}}$ is a function of T_0 , the dependency of maximum useful work on T_0 in (9) is not straightforward. Every student of thermodynamics knows that work increases with decreasing T_0 , which results from greater increase in $(\Delta_p S)_{\text{universe}}$ overcompensating decrease in T_0 . Every student also knows that work increases with increasing “peak cycle temperature” according to (3), which is a special case of (9). The general prediction of (9), however, is more subtle and includes the possibility of work being independent of peak cycle temperature for the case of reversible “combustion” cycle—which is consistent with the idea of Gibbs free energy [31].

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