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REVERSIBILITY IN SCIENCE AND IN ENGINEERING

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ABSTRACT
Thermodynamic 'reversibility in science' is associated with microscopic reversibility which prevails at equilibrium in the limit of spontaneity dissipation. In contrast, the original Carnot reversibility – reversibility in engineering – is the idea that the spontaneity in the transfer of heat from a hotter to a cooler body can be harnessed into useful work – the perfection of this operation is the reversible operation which yields maximum useful work, and thereby 'conserves' the spontaneity. Approaching reversibility in science is a simple limiting process, while reversibility in engineering is the ideal limits of real *reversible-like machines*. The Carnot limit has since been generalized into the Gibbs limit and the Landsberg limit. These reversibility limits inspire and guide the continuous improvement and creation of constructive *reversible-like processes* driven by various kinds of spontaneity.
Keywords: Carnot limit, equilibrium, Gibbs limit, maximum useful work, quasi-equilibrium process, reversibility, reversible-like processes, spontaneity, spontaneity conservation.

1 INTRODUCTION

Reversibility is a broadly used term in science and engineering: the time reversal invariance of microscopic physical laws (reversibility in physics); reversible chemical reactions and the principle of detailed balancing (reversibility in science); the reversible Carnot cycle (reversibility in engineering). In all three cases, reversibility is generally linked to a certain special characteristic of change: reversible changes involve no entropy production. Behind the common criterion of no entropy production, however, the reversibility in each of the three cases refers to phenomena of a fundamentally different nature. Taking the second case for instance, Katchalsky and Curran stated, 'the thermodynamic equivalent of a reversible mechanical process is a quasi-equilibrium or quasi-static process' ([1], p. 10); 'reversible' in that case, as used in science, is synonymous with 'quasi-equilibrium'.

Only the meaning of reversibility in a *macroscopic* world will be investigated here. Therefore, the first case of reversibility in physics – and any corresponding statistical mechanical implication and the issue of *being and becoming* in physics – will not be considered in substance other than serving as a background.

This article presents an analysis of reversibility in science and reversibility in engineering in terms of three perspectives: (i) equilibrium, (ii) the nature of change, and (iii) spontaneity. The analysis will show that reversibility in science has a meaning so fundamentally different from reversibility in engineering that there is a risk of this difference leading to Kuhnian *incommensurability* [2] in a scientific dialogue between engineers and scientists. I personally was told by a scientist colleague that he was not interested in the question 'What is a Carnot cycle?', even though he studies the entropy question in biology. The analysis will argue that this incommensurability – while it is a relatively minor problem in engineering except perhaps causing some difficulty in the teaching of thermodynamics – does pose a potential block to progress in science, especially in biological sciences.

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2 EQUILIBRIUM

Chronologically, Carnot introduced the concept of reversible processes (reversibility in engineering). The insight that a reversible process is a special idealized limit of all possible real macroscopic processes, which are irreversible, was developed by Kelvin and Clausius into the concept of absolute temperature (Kelvin), the concept of entropy (Clausius), and the law that entropy can only be produced, i.e. the second law of thermodynamics (Clausius and Kelvin).

The second law, in the form of the law of increase of entropy, was used by Gibbs to draw the inference that when an isolated system approaches a static state of equilibrium, the state is characterized by the maximization of the entropy of the system – subject to the constraint [3, 4] of constant internal energy and volume. In the case of systems subject to the constraint of constant temperature and pressure, their equilibrium states are characterized by minimum Gibbs function. The Gibbsian thermodynamics 'features [equilibrium] states, rather than processes, as fundamental constructs' ([3], p. viii). 'The single, all-encompassing problem of thermodynamics is the determination of the equilibrium state that eventually results after the removal of internal constraints in a closed, composite system' ([4], p. 26).

This Gibbsian perspective has prevailed in science and in the understanding of thermodynamics by scientists – including the meaning of reversibility. While Carnot defines reversibility as change that produces maximum useful work, in the Gibbsian perspective reversibility becomes the *condition* that prevails at equilibrium. An example of this is the equilibrium state reached by a chemical reaction: the amount of reactants that are converted to products per unit time is exactly matched by the amount of products that are converted to reactants per unit time. This is the condition of *microscopic reversibility*: known as the principle of microscopic reversibility, which was formulated by Tolman [5, 6]. When applied to a chemical reaction that proceeds in several steps, the principle is known as the principle of detailed balancing ([6], p. 163).

This association of reversibility with equilibrium is a surprising and radical transformation of the original concept, as depicted by the reversible Carnot cycle. In the original concept, reversible machines or devices are systems defined by operational principles which account for how systems can exist and function at states in *far from equilibrium* conditions. For a summary of the difference of the two meanings, see Table 1 ('equilibrium' row).

3 THE NATURE OF CHANGE

On further reflection, it is not, after all, surprising that the thermodynamics of Carnot, Kelvin, and Clausius was transformed into the Gibbsian thermodynamics in the hands of scientists. 'To use an expression of John Wheeler, the "royal high road of physics" from Galileo until Einstein was dynamics' ([9], p. 136). Through this transformation, these scientists aim to bring thermodynamics back to the paradigm of dynamics: the paradigmatic thinking in terms of reversibility in physics has radiated onto the meaning of reversibility in science.

State is the fundamental construct in the Newtonian deterministic dynamic world. It is often said (e.g. by Zeno) that this is an unchanging and static world in the sense that change is reduced to sequences of states. There is no additional meaning to the change of a system (see notes to Table 1). With a focus on equilibrium states, the Gibbsian thermodynamics transforms thermodynamics from its original point of view (which deals with real changes of irreversible processes) back to the Parmenides–Plato–Newton point of view of a static world. Irreversible processes are the temporary appearance of systems; true understanding lies in the knowledge of equilibrium states toward which all systems will inevitably end. To use the famous cave simile of Plato: once the temporary *becoming* of the *moving shadows on the cave wall* clears away, there is no real change in the *being* of the *world outside the cave* under the conditions of microscopic reversibility at equilibrium.

Table 1: The different meanings of reversibility in science and in engineering.

	Reversibility in science: reversibility 'is' *equilibrium state*	Reversibility in engineering: reversiblity 'is' *maximum useful work*
Equilibrium	Reversibility in science is understood to be the condition of microscopic reversibility which prevails for systems at *equilibrium*.	Reversible machines or devices are systems defined by operational principles which explain how systems can exist and function at states in far from equilibrium conditions.
Change and creativity	The dynamic thinking in terms of reversibility in physics has influenced the meaning of reversibility in science. There is no 'real change'* in nature and no action** in nature.	Processes of reversible machines are not reducible to sequences of equilibrium states;*** they are *designed* for the purpose of producing *maximum useful work* [7]. There is real change*** and creativity in nature.
Spontaneity	Reversibility is the limit of irreversible spontaneous processes, during the course of which spontaneity is dissipated.	Reversibility is the perfection of constructive *reversible-like changes* to harness the spontaneity in macroscopic nature. Spontaneity is 'conserved'.

Notes:
*There is no macroscopic change under the condition of microscopic reversibility. Also, there is no real change in general in the sense (Zeno) that any dynamic change is reducible to sequences of (static) states; there is nothing discernable about a system in a process of change that is intrinsically different from a system which is not changing. There is no such thing as a *state* of change.
**Reversibility describes processes that are (passive) microscopic happenings, not macroscopic actions.
***There is such a thing as a *state* of change: A quasi-static change of a system may share the identical sequence of quasi-equilibrium states as a reversible change of the same system. But the *state* (attributes) of the system during quasi-static change is different from that of the system undergoing reversible change. The latter system may be characterized by, e.g. piston rod, linkage to work reservoir, and work reservoir. The former system does not have those attributes [7, 8].

Microscopic reversible processes are just happening. There is no action, and no function or purpose of this happening.

This is radically different from the thermodynamics of Carnot, Kelvin and Clausius, which is a science founded for the consideration of the irreversible, real changes of macroscopic nature in the context of nomic possibilities of nature, as well as the construction of the ideal limit of these possible changes as reversible change. Nomic possibilities are all the possibilities that are consistent with the laws of physics. Nomic possibilities are not the same as causal or deterministic possibilities, which, as pointed out by Poincare [10] in the quotation on p. 189, belong to a subset of nomic possibilities. Things that are nomologically possible include things which are consistent with the laws of physics *and* defined by operational principles (i.e. the method of operation, or the defining characteristics, of a thing [11]).

The important inference here is not the principle of microscopic reversibility, but the maximum useful work theorem: a reversible change of a system from its initial state to its final state produces maximum useful work; any irreversible 'reversible-like change' between the same end states yields useful work less than the maximum useful work.

Such reversible processes are not reducible [7, 8, 12] to their sequences of equilibrium states (which are known as quasi-static paths [1, 3, 4]) alone. This discovery that states are not the sole fundamental construct is a direct challenge to the Newton–Laplace–Einstein static view of dynamics, which dates back to Parmenides and Zeno; irreversible and reversible changes in macroscopic nature are real [7].

In the world of real changes, new machines are novel creations, which are designed to function for specific goals and purposes. (See Table 1 for a summary of this perspective.)

4 SPONTANEITY

I now come to the third perspective of reversibility in terms of spontaneity. Historically, the second law is the general assertion drawn through both inductive and deductive reasoning from specific observations of various spontaneities in nature. A good verbal statement of the second law is that there is spontaneity in macroscopic nature, which cannot be created out of nothing and in fact will eventually dissipate. When reversibility in science is associated with the condition of equilibrium, reversibility (as well as equilibrium) is understood to be the limit of dissipation of spontaneity. Spontaneity is fated to dissipate; reversibility is the condition at that inevitability.

When an engineer looks at spontaneity, he/she does not contemplate its fate, but sees opportunity. The engineer asks whether there are ways to harness spontaneity for some purposes. He/she does not doubt the reality of spontaneity or feels powerless as a Platonist philosopher would in submitting to the deterministic reality. As Poincare [10] noted,

> [These thermodynamic laws] can have only one significance, which is that there is a property common to all possibilities; but in the deterministic hypothesis there is only a single possibility, and the laws no longer have any meaning. In the indeterministic hypothesis, on the other hand, they would have meaning, even if they were taken in an absolute sense; they would appear as a limitation imposed upon freedom. But these words remind me that I am digressing and am on the point of leaving the domains of mathematics and physics.

The engineer feels free to act, to devise, or to invent machines that will convert spontaneity into useful work. The historical engineer, Carnot, theoretically devised a reversible heat engine that produced maximum useful work from the spontaneity of a thermal reservoir. I theoretically devised a reversible heat engine [8] that produces maximum useful work from the spontaneity in a CO and O_2 mixture. Spontaneity offers an opportunity of possibilities; reversibility is the theoretical ideal of these possibilities and the action that can be taken for fulfilling that ideal.

Real heat engines are irreversible. However, they are clearly distinct from irreversible spontaneous processes toward equilibrium. An alternative set of definitions is required for macroscopic processes. While 'reversible' and 'irreversible' serve the useful purpose to point out the fundamental difference between microscopic and macroscopic processes, they would not suffice for the purpose of defining two fundamentally different types of macroscopic process.

Irreversible real heat engines are designed for the same objective as theoretically designed reversible engines. For this reason, they may be referred to as 'reversible-like processes' or reversible-like devices – *designed* to be spontaneity-driven. Consequently, irreversible spontaneous processes may be referred to as 'non-reversible processes' [7]. Reversibility in engineering is the perfection of reversible-like changes to harness the power of spontaneity in macroscopic nature into (maximum) useful work. Spontaneity is 'conserved' during the course of reversible change as understood in engineering. Reversibility in science, on the other hand, has nothing in common with reversible-like processes in this respect and, instead, is the equilibrium end-point of a spontaneity-dissipation process. (See Table 1 for a summary of this part of the discussion.)

Reversible-like processes and non-reversible processes designate two different types of change in nature: the latter are (destructive) changes toward equilibrium corresponding to 'order becoming chaos', and the former are constructive changes [7], which are driven by spontaneity in nature.

5 CONCLUSION

In sum, reversibility in science understands reversibility as the condition that prevails at *equilibrium states* in the limit of spontaneity dissipation. Thus, reversibility 'is' equilibrium state; a reversible change is a quasi-equilibrium process that is defined to be a sequence of equilibrium states. Reversibility in engineering defines reversibility as the asymptotic limit of the continuous improvement of reversible-like processes toward the ideal of spontaneity 'conservation' by producing *maximum useful work*.

A reversibility-in-science process is a nomic process. A reversibility-in-science process as a sequence of equilibrium states can be 'improved' only in the sense of making every one of the quasi-static steps smaller and smaller until they are infinitesimally small. In the limit of which either the process approaches the limit of *internal reversibility* [7, 8, 12] or the process fails to approach that asymptotic limit. That is really a limiting procedure and that limit is not the limit of reversibility in engineering [7, 8, 12]; any talk of improvement in those cases makes no sense [10].

On the other hand, reversible-like processes or devices are continuously improved and new kinds types are continuously created. Consideration of the reversibility (in engineering) limits of reversible-like processes serves the fundamental objective of inspiring and guiding the improvement and creation of constructive processes and devices. It is interesting to note the three known reversible limits of important applications (Fig. 1).

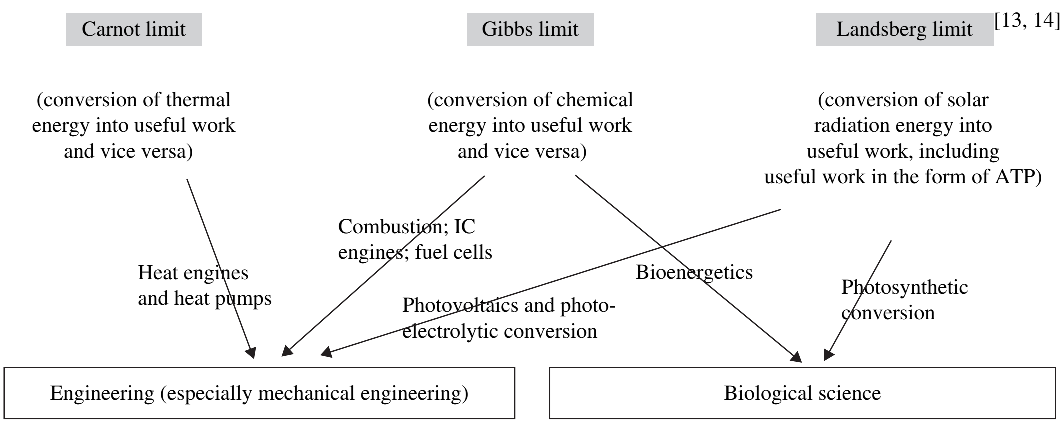

Figure 1: Reversible limits of reversible-like processes.

All three reversible limits are fundamental to mechanical engineers in their understanding and practices involving heat pump systems and nuclear power systems; fuel cell systems, internal combustion energy conversion [15], and biofuel technologies; solar energy technologies [14, 16]. Both the Gibbs limit and the Landsberg limit are fundamental to biological science in the understanding of bioenergetic and thermodynamic processes in the biosphere. These reversibility limits set conceptual limits in an explanatory framework for understanding technological novelties [14–16] and biological *endless forms* [17].

As Crabtree and Lewis [16] recently noted,

> Solar conversion is a young science. … In contrast, fossil-fuel science has developed over more than 250 years, stimulated by the Industrial Revolution and the promise of abundant fossil fuels. The science of thermodynamics, for example, is intimately intertwined with the development of the steam engine. The Carnot cycle, the mechanical equivalent of heat, and entropy all played starring roles in the development of thermodynamics and the technology of heat engines. Solar-energy science faces an equally rich future, with nanoscience enabling the discovery of the guiding principles of photonic energy conversion and their use in the development of cost-competitive new technologies.

6 EPILOGUE

6.1 The dichotomy of nature

An unanswered question in science is the apparent dichotomy of nature. Why, on the one hand, nature abounds with the disappearance of spontaneity or affinity and, on the other hand, it abounds with the emergence of 'order', 'complexity', and organization? As E. Schrodinger puts the matter, there are two great questions of life: 'order from order' and 'order from disorder'. The question considered here is of course the second question [18].

Self-organization [19] has been proposed by many as the mechanism for the emergence of organization. The paths toward self-organization are often suggested to be characterized by the tendency toward maximum entropy production – known as the maximum entropy production principle [20, 21].

There is no question that nomic self-organization processes are happening in nature, which can explain various transitory phenomena of apparent order. But, nomic self-organization processes are not the kind of constructive processes discussed in this article. In another article [7], I made the suggestion that constructive processes are necessary for the comprehension of biological phenomena, which exhibit persistent, stable organization.

I understand the division between the purposeless nomic processes (whether they are dynamic processes, microscopic reversible happenings at equilibrium, or self-organizing processes) and constructive reversible-like processes to be one that dates back to the different visions of Plato and Aristotle. Galileo, Newton, and Einstein saw their view that mathematical laws express the deep structure of reality as a continuation of the Platonic tradition [9]. In that tradition, which has completely dominated the scientific view up to this day, time is spatialized into mathematical time and there is no creativity in time. Aristotle (and I believe including Carnot, Darwin, Bergson [22] and Polanyi [11, 23]), in contrast, held the opposing view that mathematical laws are not the only fundamental constructs of reality and that there are deepest truths about the world – including time and creativity, or the metaphysics of time and creativity – which can only be expressed with languages other than mathematical languages (or new mathematical languages). Proper understanding of reversibility, which includes the nonmathematical (i.e. not in the traditional forms of mathematical laws, but still quantitative) meaning of reversibility used in engineering presented in this article, is necessary to initiate a research program on the basis of the suggested premise that reversible-like changes – rather than nomic self-organization changes – are the key to the understanding of the creative emergence of technology and biological organization.

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