Thermodynamics, entropy and disorder in futures studies

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Abstract

The conceptual bases of futures studies are constrained by physical reality only to the extent that we construct these according to our *best understanding* of physical principles. This places a burden on futures practitioners to ensure that engagement and use of these principles is sufficiently robust to protect the plausibility of their work. The second law of thermodynamics is widely recognised as having fundamental implications for the nature of our physical reality. It is also widely misinterpreted, leading to distorted understanding of this reality. Thermodynamic principles are frequently referred to in the futures literature, and are sometimes fundamental to the futures thinking underlying the work. Reflecting the widespread misunderstanding of the second law, usage in the futures literature is usually problematic. This has implications for the value of the work, and also for the credibility of the field. In this article, the problem is demonstrated, and an updated interpretation of the second law is introduced. The origin of the problem is examined from historical and scientific perspectives within the thermodynamics field. The updated interpretation's implications are examined in the context of futures and other trans-disciplinary perspectives.

1. Introduction: thermodynamics in futures studies

In a recent *New Scientist* article, Ray Kurzweil [26] draws an analogy between the predictive power of thermodynamic laws in determining the future physical properties of a gas volume, and the validity of predicting future IT capability by considering the net activity of many agents acting chaotically. The elegant simplicity of such an idea does seem attractive. Creating a conceptual link between justification for the predictability of phenomena in the human social sphere and fundamental physical laws offers comfort in the midst of uncertainty. Thermodynamic laws, and in particular the second law of thermodynamics (referred to hereafter as *the second law*), continue to represent islands of stability in a world that futurists are accepting more and more to be inherently unpredictable. Frequent references to the second law and the related concept of entropy in the futures studies literature—sometimes as essential bases for futures thinking, sometimes as an aside to remind us that there *are* inevitabilities—serve to highlight that futures studies remains grounded in the realities of a physical world. Slaughter [44, pp. 242-3] highlights just this in sketching the territory explored by his first of six questions for investigating a structural overview of the future. In response to the question "What are the main continuities?", the basic laws of physics that set the limits and conditions for life are one of the pillars to which he draws specific attention.

Even amongst the laws of physics, though, the second law holds a special significance and fascination. The astrophysicist, Sir Arthur Eddington [12, p. 74], is renowned for attributing to it 'the supreme position amongst the laws of Nature'. Of particular significance from a futures studies perspective, Eddington [12] was also the originator of the now classic aphorism describing the second law as "time's arrow". He proposed this metaphor to relate observations that we make in our daily lives, of phenomena arising in particular sequences, of processes proceeding in a consistent and locally predictable manner, to a tendency that is built into the fabric of the cosmos. It is this relationship between the second law and our experience of time upon which Bell [2], in exploring the deeper background of futures thinking, bases his conclusion that time in the physical world is unidirectional and irreversible.

Highlighting the significance of the second law, Bell [2, p. 134] writes: 'First, there is the second law of thermodynamics, the scientific equivalent, according to C. P. Snow, of Shakespeare's works of literature.' Bell's reference to Snow in *Foundations of Futures Studies* has great symbolic significance for the matters to be explored here. Bell is referring to statements made by Snow [46] in his 1959 Rede Lecture, subsequently published in book form as *The Two Cultures and the Scientific Revolution*. Snow, a physicist and novelist, was drawing attention to a breakdown in communications between those educated in the sciences and those educated in the humanities, a schism that he saw as contributing to the perpetuation of large-scale social problems. This idea is also seen, for instance, in E. O. Wilson's [51] *Consilience*, and is one driver for Slaughter's [45] development of Integral Futures Studies. The special significance of this for the present study will become clear shortly.

Bruner [6] describes in *Actual Minds, Possible Worlds* two distinct modes of thought, both used to understand experience and to convince others of the adequacy of that understanding, but each with its own unique basis for verification. The first mode relates to well-formed argument, verified by formal procedures that establish the argument's truth. The second mode relates to story, and its adequacy is established by lifelikeness, or *verisimilitude*. Of central concern here is Bruner's strong opposition to the idea that one mode is reducible to the other: both are complementary, and necessary for a thorough account of human experience.

The differentiation between a logical argument and a good story lies at the heart of this exploration of the second law in futures studies. For example, W. I. Thompson has described the second law as a modern, scientific version of ancient myths:

> The thermodynamic activity of the youthful and newly emergent gods disturbs the condition of rest and entropy preferred by the Great Mother, and so the battle of the male god, Marduk, is no longer the old Neolithic cosmology of the male as the symbol of vanishing and the female as the symbol of continuity; it is a battle of form versus entropy, of civilized, military patriarchy versus prehistoric matriarchy, of the enduring and the changeless versus transformation. All the ideas that we have since rearticulated into the Second Law of Thermodynamics have their origin in this matrix of myth. [47, p. 98]

If this is so, then a problem has occurred in the transcription process, for Thompson's story bears little resemblance to the scientific formalisms on which the second law is based. Thompson, however, is not alone: the popular mythology that poses as the second law surely represents one of the most extensive collections of misinterpretation and error to have accumulated since emergence of the scientific method. And the problem is alive and well in futures studies.

As a transdisciplinary domain, the exploratory landscape of which is by nature conceptual, the futures studies field is particularly at risk from disjuncture between science and story. Lifelikeness *and* scientific rigor are essential for ensuring that envisaged futures remain engaging and sit within the realms of the possible. This is highlighted in van der Heijden's approach to scenario planning. He specifically discusses the value of using causal-loop diagrams of the underlying system for reinforcing the internal consistency of scenario storylines [48, p. 258]. Causal-loop mapping is itself a significant futures methodology, the strength of which is dependent on appropriate understanding of causal relationships [18]. The trouble is, decisions relating to far-off futures *can* be made on the basis of lifelikeness alone:

there is no final test for whether or not our concepts of the future are consistent with empirically verifiable reality. All such tests involve some degree of interpretation.

If futures studies faces particular difficulties in grounding its work within the constraints of physical reality, then this is likely to have ramifications for the wider relevance, credibility, legitimacy and, ultimately, acceptability of our work. While focused on the specific case of the second law, the purpose of this article is to promote the more general importance of intellectual rigor and truth-seeking in futures studies, with a view to enhancing and developing the legitimacy of the field, and hopefully to stimulate continuing interest in and contribution to this enterprise within the futures studies and foresight community. In this article, the specific problems are introduced, and their origins explored from scientific and historical perspectives. A comprehensive introduction to the second law is presented based on an updated interpretation. This is then contextually linked to areas relevant to futures studies, particularly sustainability, economics and evolutionary processes.

2. An introduction to the problem, and to a response

In considering the extent of the pervasive interpretation errors surrounding the second law, Corning and Kline [10, p. 274] note that 'Entropy is now a household word for any kind of disorder, disorganization, uncertainty, waste, confusion, inefficiency and, most flagrantly, willful sabotage. Entire best-selling books have been devoted to exploring the (supposed) philosophical, ideological, economic, even social and psychological implications of the Second Law.' Lambert [30] observes that 'There is no more widespread error in chemistry and physics texts than the identification of a thermodynamic entropy increase with a change in the pattern of a group of macro objects.' This has overflowed into the writings of popular authors who 'have learned that scientists talked about entropy in terms of disorder, and thereby entropy has become a code word for the "scientific" interpretation of everything disorderly' including 'the decline of society' [29]. Add to this issue more basic errors in interpreting thermodynamic knowledge (for instance the arbitrary extension of thermodynamic laws from characteristics of energy to characteristics of matter; characterization of entropy as a *substance* or a *force*; and conflation of Shannon's information "entropy" with thermodynamic entropy) and the extent of chaos and confusion in popular, non-specialist and transdisciplinary use of this knowledge becomes clear.

Detailed examination of some specific cases will be necessary in demonstrating the nature of these problems as they appear in the futures studies literature. This task will be left until after the more general elaboration of the problem and its origins in terms of the science of thermodynamics. For now though, the breadth of the problem can be appreciated by considering some of the sources that have been found to refer to or make use of the second law in ways that are inconsistent with the current best understanding of this science. These include: in the popular or transdisciplinary scientific [Note 1] literature Capra [7], Georgescu-Roegen [15], Rifkin [40], Prigogine & Stengers [39], Daly [11], Hawking [17] and Shrödinger [43]; in the journal *Ecological Economics*, Gillet [16], Lozada [35], Krysiak [25], Ayres [1] and Kåberger & Månsson [21]; in recent issues of *Futures*, Fricker [13], Lawn [34] and Yea [52]; in the *Journal of Futures Studies*, Viik [50]; in the journal *World Futures*, Min [36], Brier [5], Knyazeva [23], Naveh [38], Robertson [41], Ceruti & Pievani [8], Colamonico [9], Montecucco [37] and Sahtouris [42]; elsewhere in futures-specific literature, Bell [2] and Jones [19,20].

The point of specifically identifying these works is not to denigrate the authors or their intentions; rather it is to draw attention to the extent of the problems involved with applying thermodynamic concepts to wider domains, and especially to work in futures studies. Even so, some of these authors have been particularly influential in shaping popular understanding of thermodynamic principles, and in doing so, encouraging the extrapolation of these principles to fields of study well beyond the contexts within which the principles were originally established. One of these authors, whose work is influential in the field of ecological economics, once wrote: ‘To explain in detail what entropy means is not a simple task. The notion is so involved that, to trust an authority on thermodynamics, it is “not easily understood even by physicists”’ [14]. It seems unfortunate that perceptions like this have not encouraged some writers to leave discussion of thermodynamic concepts to those more comfortable with their foundations.

Dr. Frank Lambert, Professor Emeritus (Chemistry) at Occidental College, Los Angeles, has for the past decade been working to redress the popular (and, in many cases, specialist) misunderstanding of the second law. Lambert makes clear that ‘Entropy is not a measure of disorder or chaos’ and that ‘Entropy is not a driving force’ [29]. The driving force in chemical (and hence biochemical living) systems is ‘Energy's diffusion, dissipation, or dispersion in a final state compared to an initial state’ [29]. Lambert’s efforts have resulted to date in at least fifteen prominent chemistry textbooks being revised to replace the “order to disorder” metaphor with an updated definition based on *energy dispersal* [33]. Lambert also reports that the eighth edition of the worldwide best-selling textbook on physical chemistry, Atkins’s *Physical Chemistry,* has been revised to significantly reduce emphasis on order-disorder, emphasising instead this energy dispersal metaphor [33].

In the revised texts:

- The second law of thermodynamics is defined as *the tendency for energy to spontaneously disperse within a thermodynamic system, or from a thermodynamic system to its surrounds, unless it is hindered from doing so* [28].
- Thermodynamic entropy is then defined as *the measure of the energy so dispersed, at a given temperature* [28].

These definitions are presented here as both the benchmarks for assessing how adequately thermodynamic concepts have been applied in the literature examined, and as proposed reference markers for subsequent work in futures studies that draws or is based on thermodynamic concepts.

3. Understanding the problem: some history and science of thermodynamics

To begin understanding the nature of the second law interpretation problem, it will be helpful to go back to basics. In the following section, the second law is considered in its scientific and historical contexts. The discussion is unapologetically technical: part of the problem that has arisen with understanding of the second law appears to be that important nuance has slowly been eroded away over time, eventually rendering popular versions meaningless. Returning to the thermodynamic roots of the concepts is an important part of setting the record straight, and will hopefully lend further credibility to the corrective account.

The discussion that follows relates to *thermodynamic systems* [Note 2], defined as systems of matter subject to transfer of motional or phase change energy at the atomic or molecular scale due to interactions between the particles comprising the system.[Note 3] A thermodynamic system consists of a quantity of matter of fixed mass and identity, and is separated from its surroundings by a defined system boundary [49, p. 16].[Note 4] In particular, a system of matter can be considered as a *thermodynamic system* where interaction of the constitutive particles is subject to thermal dominance of the particles’ environment [30]. It is in the context of observations and experiences relating to such systems that the laws of thermodynamics have been developed, and to which these laws are hence intended to apply. To extend these laws beyond such contexts is to map them onto ontological landscapes for which their empirical basis is potentially unfounded. This has important implications for use of thermodynamic principles in futures studies or in other secondary domains.

Some additional definitions will provide useful context for the discussion that follows:

- Energy is typically defined as the capacity to do work or to transfer heat. The unit of measure for energy is the joule (J);
- Work is a force applied over some distance. Its unit of measure is the joule (J);
- The first law of thermodynamics states that energy can be neither created nor destroyed – it can only be converted from one form to another;
- Entropy is an *extensive property* of thermodynamic systems, with units of measure of joules per degree kelvin (J/K). *Extensive property* means that the value of this property is proportional to the amount of matter in the system. In contrast, *temperature* is an intensive property: if a system is divided into two equal parts without any other changes occurring, the temperature of each part will be the same as the original system. The entropy of each part will be proportional to the amount of matter in each part, and the total entropy of the two parts will be the same as for the original system [49, p. 19].
- The entropy of a system is dependent on the system's state, as described by its macroscopic, measurable properties such as the temperature, pressure and mass of a given gas. Whenever a system comprising a specific substance or mixture of substances is in the same state (for instance, the temperature and pressure of a quantity of gas are the same everywhere at one time relative to another time), its entropy is the same, regardless of how the system came to be in that state [49, p. 19].

The material activity that we perceive in the course of our embodied experience with our world involves work: forces, acting on physical objects, resulting in changes to the position and form of those objects. *Energy* is an abstract concept that we have constructed in order to describe and understand the activity, or the behaviour, that we observe in the course of our interactions with material systems. Energy is not a *thing* or a *substance*: it is a conceptual construct that assists us to make sense of our experiences relating to the activity of things or substances.[Note 5] The second law simply reflects our experience of spontaneous events in which 'All kinds of energy spontaneously spread out from where they are localized to where they are more dispersed, if they are not hindered from doing so' [32].

Entropy, then, is an abstraction *of an abstraction*: it is an abstract concept that we have created to describe and understand the condition of material systems resulting from the activity of these systems that we describe in terms of energy-enabled causation. That is, entropy is a conceptual construct that assists us in describing the change in condition of material systems as a result of the activity within those systems, and interactivity between systems. It is not appropriate to consider entropy as a *thing* or a *substance*. To do so would be akin to considering temperature and pressure as things or substances: the problem associated with this will hopefully be clear. Importantly, this points towards examination of the deeper, more general cognitive and cultural roots underpinning our construction and use of abstract concepts, as a pathway to gaining a more adequate understanding of the misinterpretation problem, and hence to strengthening futures thinking.

The second law describes a general principle relating to the activity *of activity* of things, specifically as this manifests in thermodynamic systems. While it is common to say that such-and-such happened because of the second law, this reifies the second law as something that exists independent of the cultural processes by which we have constructed it in order to communicate our experience of an observed tendency. This then leads potentially to the second law being applied outside its terms of reference: we forget that it has been constructed within particular contexts or circumstances, and thus is *literally* applicable only within appropriately similar contexts. To say, for instance, “the ball rolled down the hill (thus dispersing some of its gravitational potential energy) *because of* the second law of thermodynamics” is somewhat misleading. It would be more meaningful to say “the ball rolled down the hill due to a tendency for energy to disperse”: these concepts of *energy* and *dispersion* are literally applicable both to their general domain of construction and this specific context. A ball is a macro object that is not under the thermal dominance of its environment: therefore the second law is not literally applicable here.[Note 6] Even so, many people with a basic understanding of physics would be moved to say “I know what you mean” in relation to the original statement. What is happening here is that one experiential domain is being mapped onto another in a *metaphorical* sense, indicating again the psycho-social underpinnings of the second law interpretation problem. One particular consequence bears consideration here though: Eddington’s [12] famous aphorism relating to the supreme position of the second law amongst the laws of nature becomes problematic. It would be more meaningful for Eddington to have written that *the tendency for energy to disperse, unless hindered from doing so*, holds the supreme position amongst the laws of nature.

In addressing the widespread misunderstandings relating to the second law, Kozliak and Lambert [24] trace the history of the idea that “entropy is disorder”. It is generally recognised that the origin of this is Ludwig Boltzmann’s statistical characterisation of changes in the entropy of a system as “order to disorder” [4, pp. 442-3]. Lambert [29] notes that, at the time of Rudolph Clausius’s initial definition of entropy in 1865, ‘there was considerable doubt even about the reality of atoms. Thus, the behavior of molecules or molecular groups within a macro system were (sic) totally a matter of conjecture.’ It is against this background that, ‘later in the nineteenth century, but still prior to the development of quantum mechanics, the greater “disorder” of a gas at high temperature compared to its distribution of velocities at a lower temperature was chosen by Boltzmann to describe its higher entropy’ [29]. Lambert emphasises, though, that ‘“disorder” was a crutch, i.e., it was a contrived support for visualization rather than a fundamental physical or theoretical cause for higher entropy value’ [29].

Boltzmann used the term *complexion* to describe the velocities of a collection of gas molecules [10, 29]. Boltzmann’s complexions were a precursor to the more recent (and currently favoured) concept of energetic *microstates*. These microstates are defined in relation to the corresponding concept of energetic *macrostates*. The technical discussion of thermodynamic principles necessarily deepens at this point.[Note 7] In considering what follows, it is important to bear in mind that macrostates and microstates define energetic configurations—the way that energy is distributed within thermodynamic systems. Macrostates and microstates do not pertain simply to the physical arrangement in space of the system’s particles. And, as will be shown, the term *dispersal* as used in the definitions above has a more precise thermodynamic meaning than just “spreading out in three-dimensional space” [31].

The term macrostate refers to the energetic condition of a thermodynamic system as defined by its bulk (or intensive) properties of temperature, pressure and density. A microstate is the specific energetic configuration of the atoms or molecules comprising the system, such as the kinetic, rotational and vibrational energy states of particles in a gas, at a particular instant in time. A microstate is a description of the way that quantized energy is distributed across each of the particles in a thermodynamic system, recognising that each particle in the system can exist at one level within a given range of accessible, quantized energy levels at a given instant in time. *Quantized energy* simply means that the motional energy associated with a particle can have only discrete values: the particle’s energy must change in steps of finite magnitude. Those familiar with the particle metaphor for light, in which light’s electromagnetic energy is conveyed as *photons*, or discrete packets, will recognise the similarity here. The macrostate of a thermodynamic system at any particular time consists of one of an enormous number of possible microstates. As soon as there is interaction between any particles in the system sufficient for those particles to shift to different quantized energy levels, the system will be in a different microstate. If the bulk properties of the system remain unchanged as a result of the interaction between particles, then the macrostate of the system will remain unchanged.

For any given energetic macrostate, there will be (provided the temperature of the system is at least a little above absolute zero) an enormously large number of possible microstates, one of which the system's component molecules will be in at any given instant [24]. With no change in the macrostate of the system, the system will shift from moment to moment between different microstates corresponding to that macrostate. However, a system will tend to shift from a macrostate for which there is a smaller number of accessible microstates, to a macrostate for which there is a larger number of accessible microstates, unless it is inhibited from doing so. That is, a system will tend to change spontaneously from a macrostate with a higher probability of the system occupying a particular microstate, to a macrostate with a lower probability of the system occupying a particular microstate. It is this drift that lends the arrow-like directionality to the second law. Moreover, it is the visualisation of the concept of movement from a macrostate with higher probability microstates to a macrostate with lower probability microstates to which Boltzmann applied the metaphor of "order to disorder".[Note 8] But recall: this metaphor of "disorder" applies only to the way that *energy* is distributed throughout the matter comprising the thermodynamic system. For cases in which a change in a system's entropy involves a redistribution of energy within the system, rather than a transfer of energy to or from the system's surrounds, this is commonly referred to as a change in *configurational entropy*. The term *configuration* here refers to the energetic configuration of the system, and not the pattern or arrangement of matter in the system. There are numerous common examples of simple chemical systems in which a spontaneous increase in entropy is accompanied by what might be interpreted as an increase in "orderliness", or "organisation", of the system's component particles, for instance precipitation of salt crystals from a supersaturated solution with some transfer of thermal energy from the solution to its surrounding environment. Notice, though, that this assessment of "orderliness" or "organisation" requires the presence of a subject who makes the assessment on the basis of some set of appropriately defined (and not necessarily universal) criteria for orderliness or organisation.

Before moving on to consider the second law in a futures-relevant context, one final area bears consideration. In the definition of the second law presented earlier, the phrase "unless it is hindered from doing so" is very important. This links thermodynamic behaviour of chemical systems (including living organisms) to consideration of *chemical kinetics*. Chemical kinetics deals with the rates at which chemical reactions take place. Where energy is stored in molecular bonds, dispersal of this chemical energy is dependent on chemical reactions occurring (for example, the release of thermal energy when oxygen and hydrogen react to form water, with the thermal energy then dispersing into the environment surrounding the site of the reaction). In this case, factors associated with the activation of the reaction become important in determining whether and at what rate the energy will disperse. In particular, some quantity of energy is required in order to initiate the reaction, by destabilising initially stable molecules. The products of these reactions will then exist in a more stable state, with less stored chemical energy. The key point here is that, in the absence of sufficient activation energy, the chemical energy associated with the initial molecules will not spontaneously disperse. The availability of sufficient energy for enabling activation of reactions can be a limiting factor for the rate at which the reactions proceed. The dispersal of energy, in order to be useful in understanding our observations of the world, must be considered in the context of the pathways by which the energy disperses. Lambert has highlighted that this relationship between the second law and chemical kinetics necessitates amendment of Eddington's classic aphorism describing the dispersal of energy as "time's arrow" [27]. In place of this, and allowing for the earlier insight in this article relating to Eddington's aphorism, a more complete metaphor has been proposed: the dispersal of energy 'is time's arrow, *but chemical kinetics is time's clock*', with this "clock" 'firmly restrain[ing] time's arrow in the taut bow of thermodynamics for milliseconds or millennia' [27]. The principal insight from this is that thermodynamic considerations, and especially the second law, are not *sufficient* for understanding the behaviour that we see around us. In order to be useful, these most general principles must be considered in the context of the particular situations in which we are interested. In particular, principles that only become apparent in situations involving higher-level emergent phenomena must be taken into account when we are dealing with situations relating to that higher-level of systemic emergence. This meta-principle is discussed in more detail by Corning and Kline [10]. From this, it follows that the second law alone does not account for things happening spontaneously.

4. Reinterpreting the second law: the futures studies context

The central point to take from the preceding discussion is that where Boltzmann used the metaphor of "order to disorder" to convey understanding of entropy increase in thermodynamic systems, he referred only to the way that energy is distributed through the system, and *not* to the way that the matter comprising the system is organised. It is the naïve extension of Boltzmann's "order to disorder" metaphor from the distribution of energy, to the organisation of matter, that has led to the widespread and deeply entrenched idea that "entropy is disorder", with disorder then taken as a measure of the quality of material organisation.

Thorough exploration of the full range of problems associated with use of thermodynamic concepts in the works cited earlier is well beyond the scope of this article. Nonetheless, detailed examination of select examples will be valuable in establishing the validity of the misinterpretation claims, and the prevalence of the problem in the futures literature. The approach taken here is to look at two source references for thermodynamic concepts widely cited in the futures literature and two examples from futures literature where thermodynamic concepts play a central role. These latter examples will also serve to demonstrate some of the various ways that thermodynamic concepts are considered relevant to the futures studies field.

Prigogine and Stengers's *Order Out of Chaos* [39] frequently appears as a primary source of thermodynamic concepts in futures literature. In the preface to their book, they write:

> Our scientific heritage includes two basic questions to which till now no answer was provided. One is the relation between order and disorder. The famous law of increase of entropy describes the world as evolving from order to disorder; still, biological or social evolution shows us the complex emerging from the simple. How is this possible? How can structure arise from disorder? Great progress has been realized in this question. We know now that nonequilibrium, the flow of matter and energy, may be a source of order. [39, p. xxix]

It is apparent from this passage that Prigogine and Stengers conflate the concepts of thermodynamic order and more complex material organisation. Later, they introduce the second law from a statistical perspective, stating that 'Boltzmann was the first to realize that irreversible increase in entropy could be considered as the expression of a growing molecular disorder' [39, p. 123]. As has been shown in this article, Boltzmann's original use of the terms order and disorder related to the organisation of energy within thermodynamic systems, and not to physical organisation of matter. Prigogine and Stengers suggest that an increase in a system's entropy is inconsistent with increased material organisation of that system. In fact, the opposite is true: increase in material organisation of a system involves work, and as such must be accompanied by a net dispersal of energy and hence increase in entropy of system and surrounds. This applies to thermodynamic systems regardless of whether they are close to or far from equilibrium. Considered solely from a thermodynamic perspective, processes involving the emergence of more complex structures from less complex structures are no different from processes that involve breakdown or decay of complex structures. The governing criterion for occurrence of these processes is whether or not a change in structure leads to energetic macrostates for which there is a greater number of available microstates. This criterion is independent of the perceived complexity of the resultant structure. As described at the end of section 3, thermodynamic criteria alone are insufficient for differentiating between physical-level and biological-level processes: for this we need to consider higher-level (emergent) principles of self-organisation. While this self-organisation is *enabled* by energy's tendency to disperse through systems of matter subject to the thermal dominance of its environment, self-organisation is not reducible to physical-level thermodynamic principles alone. The second law of thermodynamics describes a necessary-but-not-sufficient condition for self-organisation. As such, it has implications for all biological and social systems, but only when these are considered from a physical perspective as systems of matter and energy.

A second source of thermodynamic concepts frequently cited in futures literature is Georgescu-Roegen's *Entropy Law and the Economic Process* [15]. Works by Daly and Rifkin are derived from Georgescu-Roegen's treatment of the second law and display the same problems [11, 40]. At the heart of these problems is an unfounded extension of the first law of thermodynamics to matter as well as energy. As was shown earlier, the first law relates to the observation that energy can be neither created nor destroyed, but can be converted from one form to another. The second law relates to the observation that any conversion occurs with an efficiency of less than 100 percent, and hence with an increase in entropy of system and surrounds. Georgescu-Roegen writes:

> We may see why entropy came to be regarded also as an index of disorder (of dissipation) not only of energy but also of *matter* and why the Entropy Law in its present form states that *matter, too, is subject to an irrevocable dissipation*. Accordingly, the ultimate fate of the universe is not the Heat Death (as it was believed at first) but a much grimmer state—Chaos. [14, p. 8]

By this surely unintentional sleight-of-hand, Georgescu-Roegen smuggles in the idea that "entropy is a measure of material organisation". The basis for the extension of the first and second laws to matter is not apparent in his writing. The above statement appears to be as close as he comes to shedding light on this. He also discusses the "entropy of matter" during processes involving energy conversion without reference to the context of the thermodynamic systems containing that matter. For instance: 'From the viewpoint of thermodynamics, matter-energy enters the economic process in a state of *low entropy* and comes out of it in a state of *high entropy*' [14, p. 54]. As we saw earlier, entropy is an extensive property of thermodynamic systems: in order to discuss changes in entropy, even qualitatively, we must first define the thermodynamic system with which that change is associated. It is not meaningful to discuss changes in the entropy of matter in general, and it is never meaningful to discuss the "entropy of energy". Entropy is not a property of energy. It is not clear, either, what is meant by "matter-energy".

Lawn provides a clear example of Georgescu-Roegen's influence on the futures studies literature [34]. In an article in volume 36 of *Futures*, he claims that 'Many studies of the long-run output potential of economic systems have been based on aggregate production functions that violate the first and second laws of thermodynamics' [34, p. 2]. He then proposes an alternative production function that he claims addresses these violations, and uses this to demonstrate that 'total [economic] output declines in line with any fall in low entropy resource inputs' [34, p. 20]. This is then used to support the conclusion that 'From an ethical perspective, the present generation is obligated to operate sustainably. This requires natural capital to be kept intact and for population growth to be controlled' [34, p. 20]. The understanding of thermodynamic principles that underpins Lawn's ideas is demonstrated in the following passage:

> Consider a piece of coal. When it is burned, the matter-energy embodied within the coal is transformed into heat and ash. While the first law ensures the total amount of matter-energy in the heat and ashes equals that previously embodied in the piece of coal, the second law ensures the usable quantity of matter-energy does not. In other words, the dispersed heat and ashes can no longer be used in a way similar to the original piece of coal. [34, p. 3]

Lawn uses unsupportable versions of thermodynamic principles as the basis of economic models that are then used to support specific conclusions about present human behaviour necessary to bring about particular futures. His approach to establishing the stated conclusion appears to be based on rigorous science. However, his claim that the second law of thermodynamics precludes recycling of matter without loss simply has no basis. The pseudo-scientific tone of these statements could be seriously misleading to anyone not otherwise familiar with thermodynamic principles, and potentially lends his findings unfounded credibility.

Fricker, in volume 35 of *Futures*, claims that 'The benefits [of waste reduction and greater efficiency] are limited—fundamentally because of the disordered state (high entropy) of our wastes' and that 'Natural processes restore order (low entropy)' [13, p. 509]. Prigogine and Stengers's influence can be seen in the following passage:

> The second law of thermodynamics states that the universe is moving from order to disorder, from a high energy state to a low energy state, towards increasing entropy. The biosphere of this planet appears to contradict that law…evolutionary events within the biosphere have been far from constant—extraordinary in fact. They are achieved under conditions far from equilibrium, at the edge of chaos where life and solar energy effect remarkable transformations—transformations which move towards decreasing entropy, not increasing entropy—to high energy states and the concentration of matter…But only solar energy and life can do this. [13, p. 512]

This leads Fricker to the conclusion that 'Human technologies therefore need to be compatible with natural processes if we are to avoid the entropic fundamental' [13, p. 512]. The mistaken view that "entropy is a measure of material organisation" is used here as the basis for claiming a fundamental difference between "natural" and "human technological" processes, although it is not clear how this distinction would be made in practice. The tendency for energy to disperse unless hindered from doing so is not restricted to thermodynamic systems of human construction – it applies equally to all systems in which work is carried out, including all known biological systems. As with Lawn's claims, Fricker's intent is not in question here. Nonetheless, it is entirely spurious to claim the second law as scientific justification for futures based on biomimicry and solar energy. While the futures advocated by Lawn and Fricker may very well be preferable for a range of other reasons, it is misleading to present this as "thermodynamic fact".

More generally, the idea of "entropy as a measure of material disorganisation" has led to misconceptions ranging from "neat desks spontaneously becoming messy" (overlooking the energy dispersed by the person who messes up the desk, or by the wind that blows through the study window scattering papers), to the inevitability of "social decay" (supposedly evidenced by divorce, community dislocation and riots), to the end of civilisation through human agency that runs counter to the canon of living systems (overlooking that the human agency itself must be subject to this same canon, if the canon is to hold) [30]. This last idea seems to be part of a popular myth appearing in futures studies and related literature that incorporates many of the ideas discussed by Lawn and Fricker. The myth runs something like this: living systems (often, these are distinguished from those involving industrial-age human agency) spontaneously reduce entropy, or decrease "disorder" (using the erroneous relation "entropy is material disorder"). Industrial-age human systems bring about increase in entropy, or (again, using the erroneous definition) increase "disorder". Examples of thermodynamic "order" from the erroneous perspective are: the evolution of animals and plants; the growth and complexification of forest systems with time. Examples of thermodynamic "disorder" from the erroneous perspective: mineral deposits are mined and converted to raw materials for manufacturing industries and eventually, at the end of the product lifecycle, are discarded as waste, the whole process resulting at all stages in progressive spreading out and breaking down of formerly "ordered" matter.

Now, notice what happens if we confine ourselves to the valid meaning of the second law (energy tends to disperse, unless hindered). Living systems *can* be associated with local decreases in entropy, accompanied by net increase in entropy of system and surrounds. A plant converts some of the available electromagnetic energy of sunlight to chemical energy forms, through the provision of pathways by which photons of light can do work on molecular components of chemical systems in order to create new chemical components. This stored chemical energy is in turn used to carry out work on other molecules, for example to transport molecules through the plant's structure and to bring about new structural organisation using these molecules. Water and nutrients from soil are transported into the plant system, carbon dioxide from air is converted to carbohydrates and other chemicals. The plant transfers thermal energy to its surrounds, and in turn this is radiated into space: overall, there is a net dispersal of energy, and an increase in entropy of the plant system and its surrounds—no more, though, than would have occurred in the absence of the intervening energy conversions associated with the living plant.

The idea that living systems are somehow "entropy decreasing" or, to use terminology coined by Erwin Schrödinger, that they draw "negative entropy" from their environment, results from a confusion of the concepts of energetic order and structural organisation [10, p. 277]. All living systems use available energy for structural organisation, dispersing energy (making previously available energy unavailable for further work) and therefore increasing the entropy of the living system and its surrounding environment. It is quite possible for local decreases in entropy to occur, as work is done on some sub-system. But this must always be considered in the context of a system (or sub-system) *and* its surrounding environment: if it appears to an observer that a system is bringing about a net reduction in entropy, then this is the result of a limited perspective on the part of the observer. The observer has simply failed to consider the wider environmental context in which the local sub-system exists. By sufficiently expanding the boundary of the living system's context or situation, the observer will eventually observe a net increase in entropy of system and environment [22, p.43].

Individual plants and animals germinate, hatch or are born, then grow, flourish, wither and die. Considered individually, there is growth—complexification; organisation—and decay—breakdown; disorganisation. And within an ecosystem, there is similarly growth and decay, with individual organisms growing and decaying in cascading waves within the overall cycle of growth and decay of the ecosystem. And so on with systems of ecosystems through time, with, according to many researchers, an overall pattern or tendency for net complexification or growth in interrelationship at the level of nested systems of systems [7]. In all cases, though, this increase in complexity (defined here as increased intricacy of patterning and interrelationship between system components) is accompanied by net dispersal of energy, and increasing entropy of all constituent and encompassing thermodynamic systems and surrounds.

So what of our industrial-age systems driven by human agency? Net increase in entropy (the entropy of my hot water system and its surrounding environment increases as water is heated), with some local decrease in entropy (the entropy of the contents of my refrigerator reduces as the temperature reduces), along with complexification of material forms—communications networks, wind farms, transport systems, information systems, buildings—and breakdown of material forms—carbon dioxide from oil, coal and gas, wear of machines, discarding of consumer goods and packaging, disposal of mine tailings and industrial waste. Growth and decay, in cascading waves within the overall cycle of growth and decay of systems. And so on into systems of systems, all requiring the continuous dispersal of energy.

5. Conclusion

The point of re-examining the second law in the context of the sustainability of evolutionary systems is not to say everything is OK with the industrial age—far from it. The point is to show that there is no necessary and inherent tendency towards breakdown, *as a consequence of the second law*, in human techno-economic systems, and that the tendency for living systems to become more complex is not somehow in defiance of the second law. In fact, it is more meaningful to characterise the phenomenon described by the second law as a fundamental *enabler* of all activity, and hence of all life.

It does seem clear that human techno-economic systems are associated (in present form, at least) with a tendency towards resource depletion, in particular towards depletion of the capacity to assimilate the consequences of unconstrained economic growth back into our environment. Clearly, human techno-economic systems have the capacity to emerge in harmful forms. But if we are to find viable pathways beyond our present global ecological, techno-economic, social and cultural dilemmas, our efforts to create these better futures will benefit from the most comprehensive and thorough understandings of current realities and future possibilities that we can construct. Better knowledge of how our basic physical foundations operate is an essential part of this. Hopefully, this article makes some small contribution to improvement of one limited area of knowledge, in a way that can assist the work of the futures studies community. Far more important than contributing content in this specific area of knowledge though, the value of this article depends on drawing attention to the more pressing importance for establishing an interest in deepening intellectual rigor in futures studies. The bigger issue here is the question of how, in a massively transdisciplinary field, we can ensure that important nuance does not simply merge into the background noise as we shift focus from detailed specialisation to general, sweeping overview and back again.

To address this issue, a deeper appreciation of how rifts arise in the first place between science and narrative will be valuable. Extending the search for the origin of misunderstandings, such as those relating to the second law, to the underlying cognitive and cultural processes by which truths are made, may ultimately help us to move beyond Snow’s divide between the humanities and sciences. And by looking beyond the divide, we have the opportunity to find grounds for mutual understanding that might lead to futures work that can contribute to a profound healing of the world itself.

In closing, I hope that this article has demonstrated the value of critical reflection on the use of narrative-based accounts of scientific knowledge in futures work. I hope also that it has highlighted the value of coming to grips with the original experiences behind the language used to communicate scientific ideas, and stimulated an interest in ways that understanding of these ideas might be made more complete, more consistent and more effective for exploring our worlds and their future possibilities.

Notes

Note 1: The term *scientific* is used with caution here. In several cases, *pseudo-scientific* would be more appropriate. A frequent problem appears to be that restatements of the second law interpret earlier or original statements by assuming that certain key metaphors such as "order to disorder" have a literal meaning beyond the particular experiential basis of the originator, and hence can be applied to any situation that is subsequently perceived to involve "disorderliness". This ignores the particular nature of the phenomenon that was originally described by the metaphor of "disorder".

Note 2: There are three types of thermodynamic system: open – matter and energy can flow across the system boundary; closed – energy can flow across the system boundary, but not matter; isolated – neither matter nor energy can flow across the system boundary.

Note 3: Motional energy is energy associated with translation, rotation or vibration of particles in space. Phase change energy is the energy associated with changes from solids to liquids and liquids to gases and vice versa—a thermodynamic system can comprise matter in any of these three states, including combinations of these states [31].

Note 4: With appropriate modification of the equations used for analysis, the principles of thermodynamics can also be considered from the perspective of what is known in mechanical engineering as *control volume analysis*. Control volume analysis is used where a system involves continuous through-flow of mass and or energy, with continuity of some set of basic structural arrangements for facilitation of that flow. Typical examples where this approach is used include turbo machinery such as pumps and gas turbines (e.g. jet engines). Corning and Kline [10] propose control volume analysis as a more appropriate basis for considering the thermodynamic behaviour of living organisms, on the basis that all living organisms involve continuous (averaged over some part their lifetimes at least) through-flow of mass and energy. With control volume analysis, it is straightforward and commonplace to deal with systems that are far from thermodynamic equilibrium, with no need to introduce ideas such as Prigogine and Stengers's [39] "nonequilibrium thermodynamics".

Note 5: It can, however, be useful to consider energy as metaphorically having some of the characteristics of substances.

Note 6: Of course, the second law *is* literally applicable to another aspect of this example, but not in a causal sense: the energy dispersed from the ball is dissipated to the environment ultimately as thermal energy (heating of the air and ground). It would be literally appropriate to speak of this dispersal as being due to the second law.

Note 7: The discussion of molecular thermodynamics presented here is generally informed by Lambert [31] and also a wide range of Lambert's online publications available at http://entropysite.oxy.edu.

Note 8: Kozliak and Lambert [24] also highlight that, due to the enormous number of microstates accessible in even very small systems at temperatures just above absolute zero, in no sense is it reasonable to consider real systems at ambient temperatures to be "orderly", even when this metaphor is confined to its correct energetic usage. It is partly on this basis that Lambert advocates so strongly for doing away altogether with use of order-disorder in defining the second law of thermodynamics and thermodynamic entropy.

References

[1] R. Ayres, Eco-thermodynamics: economics and the second law, Ecological Economics 26 (1998) 189-209.
[2] W. Bell, Foundations of futures studies, vol. 1: Human science for a new era, Transaction Publishers, New Brunswick, 1997.
[3] Reference not used
[4] L. Boltzmann, Lectures in Gas Theory, SG Brush trans., University of California Press, Berkeley, 1964.
[5] S. Brier, Cybersemiotics and the question of semiotic and informational thresholds, World Futures 59 (2003) 361–80.
[6] J. Bruner, Actual minds, possible worlds, Harvard University Press, Cambridge, 1986 ch. 2, pp. 11-43.
[7] F. Capra, The web of life: a new synthesis of mind and matter, Flamingo, London. 1997.
[8] M. Ceruti, T. Pievani, The word "time"—voce "tempo", World Futures 61 (2005) 272–86.
[9] A. Colamonico, Edgar Morin and biohistory: the story of paternity, World Futures 61 (2005) 441–69.
[10] P. Corning, S.J. Kline, Thermodynamics, information and life revisited, part I: to be or entropy, Systems Research and Behavioral Science 15 (1998) 273-295.
[11] H. Daly, Steady-state economics, 2nd ed., Earthscan, London, 1992.
[12] A. Eddington, The nature of the physical world, Macmillan, New York, 1928.
[13] A. Fricker, Waste reduction in focus, Futures 35 (2003) 509-19.
[14] N. Georgescu-Roegen, The entropy law and the economic problem, in Energy and economic myths, Pergamon, New York, 1976, ch. 3, pp. 53-60.
[15] N. Georgescu-Roegen, Entropy law and the economic process, Harvard University Press, Cambridge, 1971.
[16] S. Gillet, Entropy and its misuse, I: Energy, free and otherwise, Ecological Economics 56 (2006) 58-70.
[17] S. Hawking, A brief history of time: from the Big Bang to black holes, Bantam Books, London, 1995.
[18] P. Hjorth, A. Bagheri, Navigating towards sustainable development: a system dynamics approach, Futures 38 (2006) 74-92.
[19] C. Jones, Cosmic Gaia: homeostasis and planetary evolution, in Macrohistory and macrohistorians, J Galtung, S Inayatullah eds., Praeger, Westport, 1997, ch. 2.20.
[20] C. Jones, Frail and feeble mind: challenges to emerging global consciousness, in proceedings of Global soul, global mind, global action—futuring from survival to thrival, International Conference, 2005, November 5-7, Tamkang University, pp.333-42.
[21] T. Kåberger, B. Månsson, Entropy and economic process – physics perspectives, Ecological Economics 36 (2001) 165-79.
[22] S.J. Kline, The low-down on entropy and interpretative thermodynamics: for students and teachers of the subject, DCW Industries, La Cañada, 1999.
[23] H. Knyazeva, The complex nonlinear thinking: Edgar Morin's demand of a reform of thinking and the contribution of synergetics, World Futures 60 (2004) 389–405.
[24] E. Kozliak, F. Lambert, "Order to disorder" for entropy change? Consider the numbers!, The Chemistry Educator 10 (2005) 24-5.
[25] F. Krysiak, Entropy, limits to growth, and the prospects for weak sustainability, Ecological Economics 58 (2006) 182-91.
[26] R. Kurzweil, Human 2.0: the new version is coming sooner than you think, says inventor and futurist Ray Kurzweil, New Scientist 187 (issue 2518) (2005), September 24, pp. 32-8.

[27] F. Lambert, Shakespeare and thermodynamics: dam the second law!, 2001, viewed 26 May 2006, http://shakespeare2ndlaw.oxy.edu/shakespeare2ndlaw.pdf.
[28] F. Lambert, A student's approach to the second law and entropy, 2005, November, viewed 30 January 2006, http://entropysite.oxy.edu/students_approach.html.
[29] F. Lambert, Disorder – a cracked crutch for supporting entropy discussions, 2005, November, viewed 20 May 2006, http://entropysite.oxy.edu/cracked_crutch.html (revised version of article originally published as F. Lambert, Disorder – a cracked crutch for supporting entropy discussions, Journal of Chemical Education 79 (2002) 187-92).
[30] F. Lambert, Shuffled cards, messy desks, and disorderly dorm rooms – examples of entropy increase? Nonsense!, 2005, November, viewed 20 May 2006, http://entropysite.oxy.edu/shuffled_cards.html (revised version of article originally published as F. Lambert, Shuffled cards, messy desks, and disorderly dorm rooms – examples of entropy increase? Nonsense!, Journal of Chemical Education 76 (1999) 1385-7).
[31] F. Lambert, Teaching entropy is simple – if you discard "disorder", 2005, viewed 7 May 2006, http://entropysite.oxy.edu/teaching_entropy.html.
[32] F. Lambert, Entropy is simple, qualitatively, 2005, viewed 12 October 2005, http://entropysite.oxy.edu/entropy_is_simple/index.html (revised version of article originally published as F. Lambert, Energy is simple, qualitatively, Journal of Chemical Education 79 (2002) 1241-6).
[33] F. Lambert, Entropy sites – a guide, 2006, viewed 20 January 2006, http://entropysite.oxy.edu/.
[34] P. Lawn, To operate sustainably or not to operate sustainability?—That is the long run question, Futures 36 (2004) 1-22.
[35] G. Lozada, Entropy, free energy, work, and other thermodynamic variables in economics, Ecological Economics 56 (2006) 71-8.
[36] J. Min, Evolutionary pluralism: a new system of systems philosophy, World Futures 58 (2002) 329–33.
[37] N. Montecucco, Coherence, brain evolution, and the unity of consciousness: the evolution of planetary consciousness in the light of brain coherence research, World Futures 62 (2006) 127–33.
[38] Z. Naveh, Multifunctional, self-organizing biosphere landscapes and the future of our total human ecosystem, World Futures 60 (2004) 469–502.
[39] I. Prigogine, I. Stengers, Order out of chaos: man's new dialogue with nature, Heinemann, London, 1984.
[40] J. Rifkin, Entropy: a new world view, Viking Press, New York, 1980.
[41] R. Robertson, Book review: Bird [3], World Futures, vol. 60 (2004) 629–34.
[42] E. Sahtouris, Why true globalization depends on new scientific models, World Futures 62 (2006) 17–27.
[43] E. Shrödinger, What is life? The physical aspect of the living cell, Macmillan, New York, 1945.
[44] R. Slaughter, Futures for the third millenium: enabling the forward view, Prospect Media, Sydney, 1999.
[45] R. Slaughter, Futures beyond dystopia: creating social foresight, RoutledgeFalmer, London, 2004.
[46] C.P. Snow, The two cultures and the scientific revolution, Cambridge University Press, New York, 1959.
[47] W.I. Thompson, Pacific shift, Sierra Club Books, San Francisco, 1985.
[48] K. van der Heijden, Scenarios: the art of strategic conversation, 2nd ed., John Wiley & Sons, Chichester, 2005.
[49] G. Van Wylen, R. Sonntag, Fundamentals of classical thermodymamics: SI version, 3rd ed., John Wiley & Sons, New York, 1985.

[50] G. Viik, Driving forces on the social order, Journal of Futures Studies 10 (3) (2006) 63-78.
[51] E.O. Wilson, Consilience: the unity of knowledge, Knopf, New York, 1998.
[52] S. Yea, Are we prepared for world population implosion?, Futures, vol. 36 (2004) 583-601.