Journal of **Scientific Exploration**
Anomalistics and Frontier Science

Platinum, open access journal published quarterly, and continuously since 1987 (ISSN 0892-3310)

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Manuscript Submission: http://journalofscientificexploration.org/index.php/jse/
Published by the Society for Scientific Exploration (SSE)—https://www.scientificexploration.org
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Journal of Scientific Exploration (ISSN 0892-3310), an open access, peer-reviewed journal, is published quarterly at the end of March, June, September, and December by the Society for Scientific Exploration, P. O. Box 8012 Princeton, NJ 08543 USA. The Journal is free to everyone. Print subscriptions: Society members: $60 per year, Libraries: $165 per year

Journal of **Scientific Exploration**
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Volume 36, Number 3 2022

SPECIAL ISSUE on:
Advanced Energy Concepts Challenging the Second Law of Thermodynamics
Issue Conceived by Garret Moddel

GUEST EDITORIAL

455 Sustainable Energy and the Second Law of Thermodynamics: An Introduction to the Special Issue
GEORGE HATHAWAY, D. P. SHEEHAN

RESEARCH ARTICLES

457 Thermodynamic Laws and Measurements
GEORGE HATHAWAY

464 Supradegeneracy, Anti-Superadegeneracy, and the Second Law of Thermodynamics
JACK DENUR

473 Beyond the Thermodynamic Limit: Template for Second Law Violators
D. P. SHEEHAN

484 Type-B Energetic Processes and Their Associated Scientific Implications
JAMES WEIFU LEE

493 Zero-Point Energy: Capturing Evanescence
GARRET MODDEL

ESSAY

504 Greedy, Blind, and Stupid—And Not Especially Quick Either
D. P. SHEEHAN

BOOK REVIEWS

507 *Rationality: What It Is, Why It Matters, and Why It Seems Scarce* by Steven Pinker
GEORGE R. WILLIAMS

512 Speaking of 'Pseudo-Science' Entails Scientism: The Importance of Not Being Earnest about Science
On the Fringe: Where Science Meets Pseudoscience by Michael D. Gordin
HENRY H. BAUER

ANNOUNCEMENTS

520 Bial Foundation Funding for Scientific Research
521 Bigelow Institute for Conciousness Studies Grants
522 Call for Papers
523 Author Guidelines

Cover Art: By author and illustrator Frank Nissen.

Cover Caption: The second law of thermodynamics is considered by much of the scientific community to be the most inviolable of physical principles. For more than a century, the primary touchstone for challenges to this law has been the Maxwell demon (hairy M-guy), a theoretical creature who sorts molecules at a microscopic level in ways that violate this law. Although the original demon has been vanquished, a new breed of authentic second law challenges has arisen over the last 25 years. Some of the most potent of these are presented in this special issue of *JSE*. Here they are given a fair scientific hearing, an opportunity rarely offered in mainstream scientific venues.

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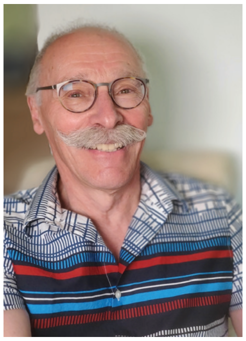
GUEST
EDITORIAL

Sustainable Energy and the Second Law of Thermodynamics: An Introduction to the Special Issue



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https://doi.org/10.31275/20222687

KEYWORDS

Second law of thermodynamics, sustainable energy, thermodynamics, science paradigm, novel energy concepts, paradigm shift

At the end of the 19th century, the field of physics was considered nearly complete, encouraging triumphal statements by some of the most eminent physicists of the day; for instance, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement" (William Thompson, Baron Kelvin of Largs).

Only a few random clouds troubled this bright horizon; for instance, the vexing negative result of the Michelson-Morley experiment (the speed of light in moving reference frames), some puzzling aspects of the photoelectric effect (light ejecting electrons from metals), and the lack of a coherent explanation for the blackbody radiation spectrum (light emitted from hot materials). There was nothing terribly serious, nothing that wouldn't be mopped up eventually. In fact, the first would soon be key to Einstein's revolutionary special theory of relativity, the second would win him the Nobel prize in physics, and the third, in the able hands of Max Planck, would crack open the door to the paradigm-shattering quantum world. Indeed, every moment is the end of physics or its beginning—depending on one's curiosity.

Viewed through the lens of Thomas Kuhn's *The Structure of Scientific Revolutions*, physics' sudden turnabout was to be expected. Whenever experts consider a field complete, beware and be amused, for it will likely erupt in revolution. This is because the nature of knowledge itself guarantees scientific paradigms will invariably germinate the seeds of their own destruction. They must. When a paradigm is established, it is incumbent upon scientists to explore it as fully as possible, to extend its domain to the fullest possible extent. This process of discovery and confirmation—the filling in of decimal places—while fleshing out the paradigm, inevitably reveals inconsistencies that must be either ignored, somehow incorporated into the paradigm, discredited and rejected, or else give rise to a new paradigm, a so-called *paradigm shift*. The latter is rarely sought or done lightly, and, in general, most scientists would prefer that it not be done at all. Paradigm shifts come in all shapes and sizes, but big ones—like the Copernican revolution, the Darwinian revolution, special and general relativity, the shift from classical to quantum worldviews—typically happen in stages that can last years, decades, or even centuries. Paradigm shifts are usually messy affairs that are costly to the instigators in the short term (years to decades), as well as to the defenders of the status quo in the long term (decades to centuries).

At the end of the 20th century, physicists were again triumphant, claiming to have finally slain the long-lived (and long-loved) Maxwell demon, the most infamous challenge to the most indisputable of physical principles: the second law of thermodynamics. The demon, a hypothetical microscopic creature, was purported to be able reorganize disorder at the molecular level and, thereby, violate the second law. Sadly, this microscopic heat fairy never actually existed and never posed any real threat to the second law; sadder still, the resolution proffered for its demise was fatally flawed, suffering from circular reasoning (Earman & Norton, 1999). Nevertheless, thermodynamicists danced gleefully on its grave.

Karmically, dancing on the demon's shallow grave summoned new and authentic threats to the second law: so-called Maxwell zombies, dozens of them (Sheehan, 2018). Some of these are found in this special edition of the *JSE*. It was time for the thermodynamic community to pick on someone its own size. And since the mid-1990s it has stepped up and done exactly what Kuhn predicted it would do: ignored the situation.[1]

The articles of this special issue of the *JSE* derive largely from the presentations at the virtual symposium *Energy Concepts Challenging the Second Law of Thermodynamics*, hosted as part of the *4th Annual Advanced Propulsion and Energy Workshop* (January 22, 2022). Additional papers were solicited from the second law examination and interpretation community. These presentations include some of the most potent and potentially commodifiable / commercializable second law challenges yet proposed.

These challenges are eclectic, drawing from the kinetic theory of gases, electrochemistry, biochemistry, and vacuum fluctuations. Two attributes link several of them, specifically: (i) physically active boundaries that facilitate the storage, control, and conversion of thermal energy into useful work; and (ii) asymmetries and broken symmetries (e.g., physical, chemical, geometric). These commonalities are tantalizing and perhaps point to a more general theory of second law challenges that has yet to be formalized.

The history of technological development indicates a general path from scientific discovery to engineering scalability, followed by commercialization, usually starting modestly; after all, *all great things begin small*. Semiconductor technology, for example, began with single transistors in the 1950s and now creates complex 2D and 3D massively integrated circuitry capable of directing many critical aspects of civilization. Given enough concentrated will, research, and development (i.e., time and money) the currently proposed second-law–violating energy systems might someday be scaled up to commercial levels.[2]

The potential implications of second law research are obvious. What is at stake is virtually all the energy in the world.[3] The total thermal energy content of the atmosphere, ocean, and upper crust is estimated to be 10,000 times greater than that of known carbon fuel and fission fuel reserves. In quantity, the energy stores of thermal energy are almost boundless and, because second-law–violating devices allow conversion of waste heat back into work over and over again without limit, the energy stores can be considered effectively infinite.

If environmental heat can be economically converted into useful work on a wide scale—electrical, mechanical, chemical—the effects on the energy sector, the global economy, societal and ecological welfare, warfare, and virtually all aspects of civilization and its relationship to Nature are difficult to predict, but they are likely to be profound—and, we hope, mostly salutary. Of course, every technology is two-edged, depending on its application.

In light of second law developments since the mid-1990s, now might seem a good time to start preparing for a world in which thermal energy will be the coin of the realm. Actually, probably not. Technological revolutions typically take decades to unfold. The carbon fuel revolution involving coal, oil, and gas took a couple of centuries to blossom fully, and the semiconductor revolution (still in progress) has taken more than 70 years to mature. Given the imperative of weaning off carbon fuels, perhaps the second law revolution will be quicker, but history, as well as the vast economic and political forces aligned against such changes, does not favor this scenario.

Despite this, it is the belief of these editors that the articles herein may offer the best hope of demonstrating a path toward engineering these second law concepts into useful energy devices. It is hoped that they will help usher in a new paradigm of inexpensive, democratically available, non-polluting, and sustainable energy production.

ACKNOWLEDGMENTS

The authors thank G. Moddel for the impetus to create this special issue of the *JSE* and are grateful to J. Houran for the opportunity to present this Guest Editorial. We also thank the anonymous reviewer for valuable suggestions.

NOTES

[1] Historically, this has usually been the case. When faced with a potential paradigm shift, the first instinct of the scientific community has been to head for the pub, have a pint, and wait for things to blow over.

[2] In the end, it may not matter whether the law is actually being violated by a particular device so long as it is net-beneficial to humanity; that is, not requiring vast amounts of expensively processed, polluting, exotic material and processes to produce useful energy outputs.

[3] This excludes energy that might be derived from the nuclear fusion of light elements (e.g., hydrogen, helium, lithium), a proposition that has consumed billions of dollars in investment as well as the some of the best scientific and engineering minds for the better part of a century and is expected to remain unfulfilled for many decades.

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Journal of
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RESEARCH ARTICLE

Thermodynamic Laws and Measurements

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SUBMITTED March 30, 2022
ACCEPTED Julne 29, 2022
PUBLISHED October 22, 2022

https://doi.org/10.31275/20222559

HIGHLIGHTS

New energy-producing concepts require novel measurement techniques, especially when these new concepts appear to violate accepted scientific principles.

ABSTRACT

This paper outlines issues associated with the verification of claims of thermodynamic law violations, focusing on measurement issues. We do not go into detail about the various interpretations and alternative forms of the thermodynamic "laws," only presenting the reader with a standard interpretation of Laws 1 & 2. The word "laws" is in quotes here as there have been recent experiments appearing to show violations of, or at least subtleties associated with, these laws which necessitate proper measurements and experimental design.

INTRODUCTION

For the purposes of this paper, the lay definition of the First and Second Laws of Thermodynamics can be summarized as:

Law 1: Conservation of Energy: [Internal/Stored energy of closed system] + [Kinetic Energy] + [Potential Energy] = difference between energy (e.g., heat) input to system and work performed (output) on or by the system or on separate system(s). Thus, *No Energy Creation*.

Note the phrase "closed system." In many claimed energy-producing devices, it is the inability to precisely define what the associated closed system is that confounds inventors. Related to this is the notion of "internal energy." Increased understanding of the role of quantum dynamics in energetic systems forces one to consider one aspect of the quantum world, namely Zero Point Energy (ZPE), as a candidate for "internal energy."

Law 2: Universal Entropy Increases: Heat spontaneously flows from higher temperature systems to lower temperature systems and not vice versa, eventually resulting in disordered, higher-entropy states. Cyclic extraction of work cannot take place while a system is embedded in a constant temperature (isothermal) bath. Thus, *No Work Without Temperature Difference*.

Recent experimental discoveries have cast some doubt on the universal application of the second law with regard to energy extraction from systems in isothermal environments. This implies that the system boundaries are known and perforce within the isothermal environment. One might also inquire whether the ZPE or universal sea of quantum fluctuations might be considered as a universal isothermal environment, for instance per the fluctuation-dissipation theorem.

Regarding the second law, the following statements of its inverse are instructive:

Kelvin-Planck "Inverse Steam Engine" statement:

It is impossible to make a cyclic device which receives heat from a single (hot) reservoir and produces work (without transferring some to a cold reservoir).

Clausius "Inverse Refrigerator" statement:

It is impossible to make a cyclic device which spontaneously (i.e., without external work) transfers heat from a cold body to a hot body.

These two statements are equivalent. Note the use of the phrase "cyclic device." Thermodynamic effects take place by transitions to and from a series of states. For instance, in a classical heat engine, where a heat source (e.g., a steam boiler) provides heat energy to a mechanical system (e.g., piston in cylinder), the pressure/volume graph of the working fluid in the cylinder proceeds from state to state and necessarily returns to the original state, or close to the original, given frictional, etc., effects. This constitutes a complete cycle, and the process can repeat ad infinitum with continual energy extraction (conversion). In classical systems, only when such cyclic systems are operating can continuous work be extracted from the heat bath. Therefore, it is important to determine by measurement whether the system returns to the original starting state if a classical heat engine is claimed to be violating a thermodynamic law by, for instance, producing "excess energy" over and above that supplied by the hot thermal bath.

Thus, some knowledge of the basic tenets of these two principal thermodynamic laws can provide guidance for the experimentalist to consider how, where, and why to perform measurements to verify claims of anomalous energy production. In particular, knowledge of system boundaries and unsuspected external influences, the contributions of stored or internal energy, the possible involvement of ZPE, whether there is actually a cold sink when a heat source seems the only option, and whether the system demonstrates a cyclic vs one-shot energy extraction are all important considerations for the verification of claims.

The thermodynamic laws are not solely associated with physical or mechanical systems. Recent work in the field of bioenergetics (Lee, 2022) indicates that certain energy processes in biological systems can apparently assist in, or perhaps be vital to, the formation of chemicals needed for life using energy from a single heat source.

PART A: EXPERIMENTS AND MEASUREMENTS

This section will present aspects of experimental design and associated measurement techniques and issues relevant to thermodynamic situations. However, such considerations can be generally applied to other scientific investigations.

Control Experiments

One important consideration in the experimental verification of potential thermodynamic law violations is the provision of control experiments. Proper experimental design requires that the actual system or device under test ("DUT") be replaced by a device that mimics the actual DUT in all aspects save that it is designed to function in a normal or prosaic manner. For example, in a DUT experiment which apparently indicates the ability to provide an anomalous thrust from on-board electrical storage apparently violating conservation of momentum (i.e., propellentless), the substitution of a control device, e.g., a resistor or capacitor for the actual DUT, should show a null result. If the control shows equivalent thrust, there is of necessity an error in the experimental procedure which allows the actual DUT to show an apparent thrust.

In the low-energy nuclear reactions (LENR) realm, say for example that someone measures a heat output from flowing gas over a specially prepared palladium substrate in apparent agreement with a theoretical prediction about some physical aspect of the metal's surface. A typical control experiment may be to alter the metals' surface characteristics to guarantee a null heat result. If a similar heat signature results, it is highly likely that the test procedure is flawed.

The proper design of control experiments requires much thought and planning and is usually foregone in many experimental programs. However, it is essential to have at least one solid control experiment to demonstrate that the experimental apparatus is performing as expected and that artifacts and prosaic explanations are either nonexistent or their influence has been calibrated and can be removed from the data representing the actual DUT's performance.

Calibration

Typically, the notion of calibration applies to the measuring instruments used to confirm the validity of claims. However, calibration necessarily also applies to the use of the correct instruments for the measurement job. For instance, when a claim is made that a device produces nanowatts of "excess energy," the correct instruments must be chosen prior to their calibration for the sensitivity, etc., of the measurements at hand. This seems an obvious point, but this association is sometimes overlooked. In many situations, a typical commercial multimeter is used in place of an oscilloscope when a non-sinusoidal AC waveform is being measured. This can lead to serious measurement errors. It is always necessary to have at least some reasonable and reliable standards of frequency, voltage, current, resistance, temperature, etc., against which to calibrate the measuring instrument at the amplitudes, frequencies, etc., of the expected signals. Generally, the highest standards are derived from the National Institute of Standards and Technology (NIST) and include reference codes related to NIST. In the absence of NIST or NIST-derived standards (called "secondary reference standards"), having two or more similar instruments giving the same readings is at least better than nothing.

The two important considerations noted above can be summed up as "No Calibration, No Control: No Claim."

Prosaic Explanations

In addition to the above issues, it is important to consider how likely it is that the anomalous measurements are the result of prosaic explanations which were not immediately obvious at the start of the experimental program. In most cases, prosaic or artefactual explanations are those which are obvious in hindsight and are the result of normally understandable processes without the need to invoke unusual or exotic explanations. Some of these artefacts are summarized in Part B of this paper. It is typical that as the experiments proceed within a program or campaign, some of these prosaic explanations start to become obvious, necessitating additional experimentation.

Thermodynamic Laws and Energy Inventions and Concepts

Energy inventions and novel concepts appear at all scales. There are a few experiments apparently demonstrating anomalous energy effects at the quantum scale (Moddel et al., 2021), the scale of biological proteins (Lee, 2022), materials and surface interactions (Thibado et al., 2020) and at larger scales (LENR, no date). At larger scales, examinations of thermodynamic laws are more relevant to the first law. This is because system boundaries are more easily defined and artefacts more easily accounted for. For instance, in a system of permanent magnets and wires, a large-scale system, the identification of prosaic explanations for the claimed violation(s) is a relatively easy task.

At the micro scale of energetic interactions, examination of the second law issues is more relevant, although it is more difficult to define system boundaries and design true control experiments.

Laws, Claims, and Measurements

Typically, claims of thermodynamic law violations result from:

— faulty or incomplete measurements (by far the most prevalent)

— incorrect system boundary definitions

— spurious and unaccounted for energy inputs, including stored energy

— under-accounting for the energy inputs

— reliance on earlier (and disproven) results.

Later in this paper, some of the usual energy measurement issues and pitfalls will be addressed. The definition of boundaries relevant to the system under examination is associated with accounting for all energy inputs and outputs. For instance, some highly sensitive force measurements on Earth may not have accounted for Coriolis effects. Often, the experimenter overlooks or ignores the fact that the laboratory in which the investigation is being undertaken is itself immersed in a sea of mechanical vibrations, tidal forces, spurious EM radiation, ZPE, etc.

Confirmation bias can also blind the experimenter to other explanations for their alleged thermodynamic law violations.

In some situations, there is a difference in approach between demonstrating thermodynamic law violations, particularly the second law, and proving anomalous energy input/output ratios. This is the case, for example, in systems claiming to produce work from a single heat bath.

Many inventors of lab-scale energy systems involving components such as magnets, coils, switches, etc., fail to realize that there have been more than 150 years of experimentation with such attempts at providing "over-unity" devices, all of which have failed. That does not seem to deter them as they point to examples on the internet claiming to have successfully replicated previous "over-unity" devices, without realizing the poor quality of these measurements and other features.

Questions to Ask Prior to Undertaking a Test Campaign to Verify Existing Claims

— *Who is the test for*: An inventor trying to convince him/herself or an investor that their idea has merit; an investor looking for confirmation of an inventor's claims; publication, fame? The distinction may be important as the level of detail required of the test campaign may vary depending on the target audience.

— *Design of suitable test bed for each project*: Is the experiment going to be conducted under circumstances related to the expectation of the inventor or the investor, i.e., "real world" situation or under a controlled laboratory situation?

— *Replication vs reproduction*: Regarding the development of a test protocol, will the experiment be an exact replica of the original invention or a reasonable reproduction of essential elements but allowing for better measurements?

— *Costs of new equipment vs re-use of existing equipment:* In many cases, the costs to verify claims can be prohibitive in terms of specialized measurement equipment, environment factors (screen rooms, temperature and humidity rooms), and other issues. A reasonable assessment of existing equipment can usually reduce costs if suitable adaptations and re-calibrations are performed.

— *Cost/benefit of simple "look–see" experiments without or prior to full testing*: Sometimes a less intense test series is warranted rather than a full-up test campaign. This depends on the urgency and whether a yes/no answer is required. This type of test should be performed with the understanding that a full test will be undertaken eventually.

— *Hypothesis generation vs hypothesis testing:* Hypothesis generation is the elucidation of alternative explanations for an observed system. It is based on observed physical phenomena without prior theory. Hypothesis testing represents the confirmation or denial of prior theory of the system's operation. Each of these requires a different approach to the design of the experimental program. Typically, hypothesis generation is more time-consuming as the extent of the experimental parameter space is unknown.

— *Enumeration of likely prosaic/artefactual explanations*: As has been alluded to, careful thought regarding prosaic explanations for the expected results prior to the experimental campaign will save a lot of headache and time during and after the experiment.

— *Design of proper and appropriate control experiments*: This requirement cannot be stressed enough. It is through proper control experiments that prosaic explanations can be accepted or rejected as explanatory to the experimental outcome.

— *Degree and sophistication of statistical and error analysis required*: Rigorous scientific experiments require that error bars, standard deviation, P values, or other statistical measures be associated with the principal outcome(s) of the experiment. In some experiments these are used to rule out the result as being obtained simply by chance. In most energy-related experiments, however, these measures tell the experimenter how "loose" the experimental procedure has been, and point out the areas that, if performed with more precision, would result in increased confidence in the outcome.

— *Instrument appropriateness and calibration*: Is the instrumentation proposed to measure the various parts of the experiment fit for purpose? A simple RMS-responding meter may not be appropriate for the measurement of spiky waveforms.

— *What minimum resolvable measurements are required to prove the claims*: This aspect is associated with instrument appropriateness as well as whether the proposed experiment is a simple "look–see" or more rigorous. The minimum resolvable measurements usually are decided by critics or reviewers of the experiment but should be elucidated prior to the experimental program if possible. This feature is typically invoked when an experiment is proposed which is designed to validate a similar but previous experiment, that is, how much more resolution will be necessary to prove or disprove the results of a prior experiment?

Measurement, Uncertainty, and Decision-Making

We enter into an experimental program to answer questions about nature, to make decisions about how and whether to proceed with an experimental program, as well as to decide the next stages of development after the experimental phase. Fortunately, most of the properties relevant to the thermodynamic analysis of forces, thrusts, electrical power, and energy and heat are amenable to quantitative measurement. Measurements can be seen as vital to minimizing experimental uncertainty. If there was no uncertainty in nature, there would be little need for experimentation. Thus it is imperative to highlight measurement issues such as those enumerated above, which factor into the evaluation of uncertainty. Also vital is the ability to transfer the experimental protocols and measurements from the experimenter to interested parties such as investors, reviewers, and other scientists.

Additional Factors for a Successful Experimental Campaign

— *Consider all relevant explanations:* Just because an explanation for the observations seems far-fetched, if the observation appears to violate thermodynamic laws the explanation should be taken seriously.

— *Design the simplest measurements that will validate (or not) the claims*: Layering on extra measurements not designed to answer the fundamental question being asked (e.g., what is the uncertainty in this measurement of potential thermodynamic violation?) leads to a dilution of attention.

— *Ensure sufficient information is available before embarking on a test campaign*: Often an inventor will either wittingly or unwittingly fail to mention certain vital aspects of the system under investigation. Sorting this out is hard to do at the beginning of a program but usually becomes obvious as the program proceeds.

— *Beware of confirmation bias*: Confirmation bias plagues many experimental programs involved in novel or exotic physics, especially in systems that may violate one or another thermodynamic law. One's own views about why an observation appears to conform to one's prior belief should be absent from an unbiased experimental program.

— *Concentrate on claims backed up with a reasonable theory*: Although there are many instances where a proposed experiment is not preceded or accompanied by some sort of theory, it is always preferable if even a rudimentary theory is available. The experiment is not only for the benefit of proving, disproving, or amplifying a theory, but also a theory can guide the experimental program to seek out alternative explanations in a more structured manner.

— *How to handle the influence of quantum effects*: Recently there has been a raft of experimental work claiming to involve zero point energy (ZPE), zero point fluctuations, quantum field energy, or whatever moniker is appropriate. This is largely due to increased sensitivity and decreasing scale of experimental apparatus over the past couple of decades. The actual influence of ZPE on quantum and microscopic systems has been well-documented and understood. However, these systems have, until recently, not allowed investigation of energy generation or energy throughput questions. Many have considered trying to drive a quantum system below the ground state. Even with today's sophisticated experimental apparatus, it is difficult to experimentally prove that a particular quantum system has been so driven. Therefore, experimentally addressing the claim that a certain energy-producing system derives its anomalous energy output by sub-ground state quantum effects can be a huge experimental challenge. Experimental tools to address this challenge are still in their nascent stage.

PART B: PITFALLS

Nightmares in the Art of Measuring: Power and Energy or "What Could Possibly Go Wrong?"

What follows is a continually growing list of pitfalls into which the experimenter can stumble regarding the measurement of electrical and mechanical power, energy, and heat. Most of them will be obvious but a more-or-less comprehensive list is at least useful as a reference. The major themes can be summarized according to the following. Due to the size of the list, only the main topics will be enumerated. The diligent researcher can find more detailed explications in the literature.

I. Electrical Power and Energy
II. Mechanical Power and Energy
III. Heat
IV. Electric/Magnetic Screening
V. Electromagnetic Effects: Electromagnetic Coupling
VI. Electromagnetic Effects: Grounding/Earthing
VII. Electrostatic and Related Effects: Charge Pooling and Induced Charges
VIII. Electrostatic Effects: Charge Leakage
IX. Instrumentation Issues
X. Signal Analysis

I. *Electrical Power and Energy*

1. DC
    - DC as heat equivalent
    - "Pulsed DC" and ringing waveforms
    - High voltage effects: circuit effects, environmental effects
    - Sources and loads—resistance matching
    - Power measurement using passive components (e.g., resistors)
2. Low Frequency (DC—few KiloHertz)
    - Active and reactive power
    - Power factor
    - Nature loves sinusoids—so do electron-pushing meters
    - RMS as equivalent heating value and power measurement
    - Non-sinusoidal waveforms & importance of visualizing (e.g., oscilloscope)
    - Sources and loads, including absorption vs transmission power measurements
    - Concept of impedance and matching
    - Instrumentation, including shielding and grounding
3. High Frequency (few KiloHertz—few GigaHertz)
    - Skin depth and effects
    - Spikes and noise
    - 2-way power flow
    - Transmission lines
    - Linear passive devices act strangely (e.g., resistors look like caps, etc.)
    - Power measurement
    - Sources and loads
4. Microwaves
    - Where is the power?—coax and waveguides
    - Reflections and impedance mismatch
    - Sources and loads
    - Power measurement e.g., bolometric calorimeter

II. *Mechanical Power and Energy*

1. Types of mechanical power—rotation, reciprocation, thrust, pressure

2. Torque and RPM
3. Sources (e.g., motors, pneumatics, springs) and loads (e.g., friction, weights, inertia)
4. Instrumentation: load cells, torque sensors, dynamometer, scales and balances
5. Conversion between electrical power and mechanical power
6. Devices, e.g., motors, generators, magnetic systems, capacitive systems, piezo systems
7. Instrumentation and comparable units (e.g., mechanical hp vs electrical kwhr)

III. *Heat*

1. Contact vs remote thermal sensing
2. Remote IR thermography, emissivity, diffusivity
3. Calorimetry and heat localization
4. Types, uses, and limits of thermocouples, RTDs, thermistors
5. Optical pyrometry
6. Optical spectrometry

IV. *Electric/Magnetic Screening*

1. Leaking/improperly sealed "Faraday Cage" / electrostatic screens
2. Improper reliance on Faraday Cage for complete exclusion of DC or quasi-static electric fields
3. Inability of screen-type Faraday Cage to screen magnetic fields therefore "muMetal" screens
4. Frequency dependence of Faraday Cage—need for calibration over wide frequency range
5. Improper feedthroughs into and out of Faraday Cage

V. *Electromagnetic Effects: Electromagnetic Coupling*

1. Avoidance of switching transients especially in high-power circuits, especially sudden stopping of current though inductive loads or conductors producing EMP inducing large spurious signals even through shielded coax or aluminum instrument boxes/cases
2. High-frequency RF radiation from nearby transmission lines or conductors especially those powering or recording the experiment interfering with electronics and electronic-based measuring instruments
3. Lack of RF suppression on power and instrument lines, e.g., ferrites, shunting caps, proper RF connectors and cables, unless disallowed for frequency response reasons
4. Avoidance of capacitive coupling between signal cables and grounds/ground leads carrying transient/fault currents
5. When a source is incorrectly matched to a load, a greatly increased level of EMI across a broad frequency range may be generated as the reflected power interferes with the correct operation of the source (usually an amplifier). This in turn may induce spurious currents in electronic measuring instruments.

VI. *Electromagnetic Effects: Grounding/Earthing*

1. Avoidance of contact potentials developing across multiple connections. In some cases, contact potentials must be compensated by a deliberately applied counter potential.
2. Strive for single-point RF ground system for all instruments and experiments.
3. Correction of ground loops and ground faults both internal to the experiment and between experiment and measuring system
4. Understand the difference between independent earth ground (e.g., copper stake in virgin earth) vs mains "ground" vs mains neutral, and potentials between these.
5. Poor/loose ground connections: preventing complete charge draining; allowing transient voltage artifacts on recording & display devices; allowing small signals to be amplified by amplifiers along with the signal of interest, etc.
6. Use of large cross-section circular wire or flat ribbon strip from experiment and/or instrumentation to earth, especially for pulsed high-power experiments

VII. *Electrostatic and Related Effects: Charge Pooling and Induced Charges*

1. Accumulation of invisible pools of surface charges on insulators on conductors. Especially problematic for metal enclosures/surfaces which have unavoidable insulating metal oxide layer formed on surface, e.g., aluminum
2. Accumulation of surface charges on water patches on inner surfaces of vacuum chambers and components even when evacuated to apparently high vacuum
3. Accumulation of charge on insulating or non-conductive surfaces, e.g., wire insulation, after exposure to electrostatic and sometimes time-varying electric fields
4. Reaction against image charges created on conductors

VIII. *Electrostatic Effects: Charge Leakage*

1. Unaccounted-for corona or other uncontrolled charge leakage usually in bursts ("Tricel Pulses") in

high-voltage experiments which can create time-varying charge on nearby conductors. Especially problematic at sharp corners

2. Avoidance of triple points—spurious conduction paths at junctions of 2 or more states of matter, e.g., corners, junctions of differing materials and gas
3. High voltage creation of weak conduction paths between device under test and ground even across or through insulators. Depends on humidity, vacuum

IX. *Instrumentation Issues*

1. Modern vs "antique" instrumentation, digital vs analog true signal bandwidth
2. Match the instrument to the job.
3. Proper connection of instrument to the job
4. Probes and accessories
5. Controlling and recording the results e.g., LabView
6. Overload and saturation
7. Frequency response
8. Matching to other instruments
9. Sampling rate, aliasing, and related errors
10. Internal math functions accuracy
11. Measurement outside specifications of instruments including sensing/measuring instruments, signal processors/amplifiers/ conditioners, and recording/display/acquisition devices. Usually applies to measurement of fast transients, e.g., pulsed waveforms
12. Lock-in amplifier response to high-amplitude transients riding on input lines causing artifacts even when not phase locked to the reference signal
13. Voltage sags/surges resulting in poor mains power quality, e.g., startup of nearby large rotating equipment

X. *Signal Analysis*

1. Correct use of averaging to tease out buried signals and suppress noise
2. Statistical Analysis: use of Chi^2, calculation of correlation coefficients, sigmas, etc.
3. Noise SNR: Is noise floor burying signals of interest?
4. Error analysis and error propagation: How confident that signal is inside measuring instrument range and that it is real—requires full specs of instrumentation or independent calibration.
5. Exploiting adjustable parameters:
   1) Adjusting phase of various parameters to detect artifacts
   2) Suppression of common-mode noise
   3) Alternate mechanical orientation of experiment with respect to possible local forces or sources

IMPLICATIONS AND APPLICATIONS

The ability to detect and measure smaller and smaller forces, currents, charges, wavelengths, etc., has allowed increasing experimental sophistication resulting in new insights into nature in general and thermodynamics in particular. Without these new understandings based on proper measurement and application of the above-noted principles allowing re-examination of the applicability of thermodynamic laws, humanity's energy future looks increasingly uncertain.

ACKNOWLEDGMENTS

I am indebted to the following persons who have assisted in assembling the list of pitfalls: Scott Little, Institute for Advanced Studies, Austin, Texas; and Bruce Towe, Arizona State University.

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Journal of
Scientific
Exploration

Anomalistics
and
Frontier
Science

RESEARCH ARTICLE

Supradegeneracy, Anti-Supradegeneracy, and the Second Law of Thermodynamics

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SUBMITTED July 2, 2022
ACCEPTED August 9, 2022
PUBLISHED October 22, 2022

https://doi.org/10.31275/20222671

HIGHLIGHTS

Supradegeneracy is argued to subvert the Second Law under certain conditions. But the simple supradegenerate system that we consider does not, even though it fulfills two conditions that we hypothesize. This online paper is a corrected revision of the print version.

ABSTRACT

Supradegeneracy—degeneracy $G(E)$ increasing with increasing energy E faster than the Boltzmann factor $e^{-E/kT}$ decreases with increasing E—has been investigated with respect to its possibly engendering challenges to the Second Law of Thermodynamics. Supradegeneracy *alone* does *not* challenge the Second Law: Systems manifesting supradegeneracy yet compliant with the Second Law are ubiquitous. If there is to be even the possibility that a system manifesting supradegeneracy can challenge the Second Law, *additional* requirements over and above supradegeneracy *per se* must *also* be fulfilled. We hypothesize what *prima facie* seem to be the two most obvious of these additional requirements. We then consider a simple system manifesting supradegeneracy and also fulfilling these two requirements. At least for the system that we consider, the answer seems to be negative: The Second Law seems *not* challenged. But understanding why the answer is at least apparently negative for the supradegenerate system that we consider may help in understanding of what at least *prima facie* seem to be positive results via analyses, including computer simulations but to the best knowledge of the author at the time of this writing not yet experimental tests, of other supradegenerate systems: of what is the *minimal complete set* of *additional* requirements—over and above supradegeneracy *per se*—that must be fulfilled by a supradegenerate system if it is to challenge the Second Law. Moreover, *even if* it turns out that *all* supradegenerate systems do *not* challenge the Second Law, they could still be useful *even within* its strictures. The same principles apply with respect to both supradegeneracy and *anti*-supradegeneracy [degeneracy $G(E)$ decreasing with increasing energy E], so a brief discussion of anti-supradegeneracy suffices. It is followed by proposal of simple experimental tests of our system: I hope, albeit probably in vain, to be proven *wrong*: Only *experiments*—the final arbiter—can decide the issue for sure! Concluding remarks are provided describing implications *if* the Second Law could be violated *by any means whatsoever* (supradegeneracy, anti-supradegeneracy, and/or otherwise).

KEYWORDS

Degeneracy, supradegeneracy, anti-supradegeneracy, Second Law of Thermodynamics, additional requirements, Boltzmann distribution, canonical distribution, Boltzmann factor, law of isothermal atmospheres, spontaneous momentum flow

I. INTRODUCTION

The probability $P(E)$ that a particle in thermodynamic equilibrium with a heat reservoir at temperature T has a given energy E is proportional to (i) the degeneracy $G(E)$ of the energy level E of the *particle*, i.e., the number of states comprising this level, and (ii) the Boltzmann factor $e^{-E/kT}$, where k is Boltzmann's constant. The Boltzmann factor $e^{-E/kT}$ is proportional to the degeneracy $G'(E_{\text{total}} - E)$ of the energy level $E_{\text{total}} - E$ of the *heat reservoir*, corresponding to the particle having energy E and hence the heat reservoir having energy $E_{\text{total}} - E$; the total energy of the particle-plus-heat-reservoir system being E_{total}. Thus

$$P(E) = \frac{G(E)\, e^{-E/kT}}{\sum G(E)\, e^{-E/kT}} = \frac{G(E)\, G'(E_{\text{total}} - E)}{\sum G(E)\, G'(E_{\text{total}} - E)} = \frac{GG'}{\sum GG'} = \frac{G''}{\sum G''}. \qquad (1)$$

In Equation (1), the unprimed quantities refer to the particle, the primed ones to the heat reservoir, and the double-primed ones to the combined particle/heat-reservoir system. The third step of Equation (1) shortens notation. The degeneracies in the numerators of Equation (1) are those of *specific*, i.e., *individual*, energy levels; the sums in the denominators of Equation (1) are over *all* energy levels. The last step of Equation (1) assumes weak coupling between the particle and the heat reservoir, which is obtained in most if not all practicable particle/heat-reservoir systems, and which we assume. [If the coupling is not weak: (i) the states of the particle and heat reservoir are at least somewhat correlated, so $G' < GG'$ and (ii) owing to the interaction energy between the particle and the heat reservoir, E_{total} is slightly less than the sum of the energies of the particle and the heat reservoir.]

Supradegeneracy—degeneracy $G(E)$ of the energy level E of the *particle* increasing with increasing energy E faster than the Boltzmann factor $e^{-E/kT}$ decreases with increasing E—has been investigated with respect to its possibly engendering challenges to the Second Law of Thermodynamics (Sheehan & Schulman, 2019; Sheehan, 2019, 2020a, 2020b, 2001–2022, 2018–2022).

But supradegeneracy *alone* does *not* challenge the Second Law: systems manifesting supradegeneracy yet compliant with the Second Law are ubiquitous. If a system manifesting supradegeneracy is to challenge the Second Law, *additional* requirements over and above supradegeneracy *per se* must *also* be fulfilled. As of this writing, it is not *completely* evident to the author what these additional requirements are. However, re-emphasizing that systems manifesting supradegeneracy yet compliant with the Second Law are ubiquitous, it *is completely evident* that they *must* exist. But we will provide tentative educated guesses, i.e., tentative conjectures, concerning what on the face of it seem to be the two most obvious of these additional requirements.

Any system with sufficiently many degrees of freedom that is compliant with the Second Law is nonetheless supradegenerate with respect to all energies less than its most probable energy (Reif, 2009, sections 2.4, 2.5, 3.7; Kittel, 2004, section 11). And "sufficiently many" does not have to be much larger than unity. The *three*-dimensional Maxwellian distribution for thermal translational kinetic energies—which is certainly within the strictures of the Second Law—manifests $G(E) \propto E^{1/2}$ and hence is supradegenerate with respect to all thermal translational kinetic energies less than the most probable one $kT/2$, at which $E^{1/2}e^{-E/kT}$ is maximized [$P(E)$ *in*creases with increasing E if $0 \leq E < kT/2$] (Reif, 2009, section 7.9; Kittel, 2004, section 13). But, by contrast, the *one*-dimensional Maxwellian distribution for thermal translational kinetic energies—which also is certainly within the strictures of the Second Law—manifests $G(E) \propto E^{-1/2}$ and hence is *anti*-supradegenerate with respect to *any* thermal translational kinetic energy [$G(E)$ *de*creases with increasing E and hence $P(E)$ decreases with increasing E *faster* than the Boltzmann factor $e^{-E/kT}$ for *all* E] (Reif, 2009, section 7.10). The *two*-dimensional Maxwellian distribution for thermal translational kinetic energies—which also is certainly within the strictures of the Second Law—manifests $G(E)$ independent of E and hence is a borderline case [$P(E)$ decreases with increasing E exactly as the Boltzmann factor $e^{-E/kT}$ for *all* E] (Garrod, 1995, exercise 1.18).

Thus our two tentative *additional* requirements: (R1) Supradegeneracy must obtain with respect to *one* degree of freedom. (R2) The pertinent energy associated with this *one* degree of freedom must a *potential* energy. R1 is at least partially justified in light of the immediately preceding paragraph. R2 is at least partially justified because, at thermodynamic equilibrium, *kinetic* energy is *in*dependent of position. Hence only *potential* energy can modify probabilities as a function of position (Garrod, 1995, exercises 7.29, 7.30; Tolman, 1987).[1] *Even if* R1 and R2 are among the valid additional requirements, they can*not* be the *only* two, because there exist systems manifesting supradegeneracy and that *also* fulfill them yet do *not* challenge the Second Law. But hopefully our hypothesizing R1 and R2 as *necessary but not sufficient* additional requirements seems at least a step forward. We denote by R* the *minimal complete set* of *additional* requirements (tentatively conjectured to include R1 and R2)—over and above supradegeneracy *per se*—that must be fulfilled by a supradegenerate system if it is to challenge the Second Law.

For example, any spontaneous endothermic (physical, chemical, nuclear, etc.) process manifests supradegeneracy and *also* fulfills both R1 and R2—yet is Second-Law–*compliant*. Let ΔE be the energy difference between a lower-energy reactant configuration and a higher-energy product configuration. Note that: (i) In accordance with R1, the reaction coordinate (the extent of reaction toward completion) represents *one* degree of freedom. (ii) In accordance with R2, ΔE is a *potential*-energy difference: at thermodynamic equilibrium with a heat reservoir at temperature T, both reactant and product species have equal thermal translational *kinetic* energies per degree of freedom. Let G_{rct} and G_{prd} be the degeneracies of the reactant configuration and product configuration, respectively. Then the equilibrium constant for this process if occurring at thermodynamic equilibrium with a heat reservoir at temperature T is

$$K_{\mathrm{eq}} = \frac{G_{\mathrm{prd}}}{G_{\mathrm{rct}}} e^{-\Delta E/kT}. \tag{2}$$

If $\frac{G_{\mathrm{prd}}}{G_{\mathrm{rct}}} > e^{\Delta E/kT}$, $K_{\mathrm{eq}} > 1$: the endothermic process is *spontaneous*, i.e., driven by the Second Law *via supradegeneracy*, *despite* both R1 and R2 *also* being fulfilled. Indeed, if the products are swept away from the reaction vessel, G_{prd} increases almost without limit: Hence for all practical purposes

$$\frac{G_{\mathrm{prd}}}{G_{\mathrm{rct}}} e^{-\Delta E/kT} \to \infty \implies K_{\mathrm{eq}} \to \infty, \tag{3}$$

i.e., the Second Law drives the endothermic process to completion *via extreme supradegeneracy*, *despite* both R1 and R2 *also* being fulfilled.

There are innumerable other examples as well, including the system that we will consider.

In Section II, we consider a simple system manifesting supradegeneracy. At least for the system that we consider, the answer seems to be negative: *despite supradegeneracy* and *despite* both R1 and R2 *also* being fulfilled, the Second Law is at least apparently *not* challenged.

Two points: (i) Understanding why the result is at least apparently negative for the supradegenerate system that we consider may help in understanding what at least *prima facie* seems to be positive results obtained via analyses, including computer simulations but to the best knowledge of the author at the time of this writing not yet experimental tests, of other supradegenerate systems (Sheehan & Schulman 2019; Sheehan 2019, 2020a, 2020b, 2001–2022, 2018–2022): of what is the *minimal complete set* of *additional* requirements R* (tentatively conjectured to include R1 and R2)—over and above supradegeneracy *per se*—that must be fulfilled by a supradegenerate system if it is to challenge the Second Law. Moreover (ii) *Even if* the negative result for the supradegenerate system that we consider *does* turn out to be similarly true for *all* systems manifesting supradegeneracy, such systems could still be useful *even within* the strictures of the Second Law (Sheehan & Schulman 2019; Sheehan 2019, 2020a, 2020b, 2001–2022, 2018–2022).

In Section III, implications pertinent to the Second Law are discussed.

In Section IV, we provide a brief discussion of (i) *anti*-supradegeneracy: $G(E)$ *de*creasing with increasing E and hence $P(E)$ decreasing with increasing E *faster* than the Boltzmann factor $e^{-E/kT}$ and (ii) *strong* anti-supradegeneracy: $G(E)$ *decreasing* with increasing E *faster* than the Boltzmann factor $e^{-E/kT}$ and hence $P(E)$ decreasing with increasing E *faster* than the Boltzmann factor $e^{-E/kT}$ *squared*, i.e., faster than $e^{-2E/kT}$. The same principles apply with respect to both supradegeneracy and anti-supradegeneracy (whether strong or not), so a brief discussion of anti-supradegeneracy suffices. We show that modifying our system so as to exploit anti-supradegeneracy (indeed *strong* anti-supradegeneracy)—either alone or together with supradegeneracy—makes no difference in our results.

In Section V, simple experimental tests of the system discussed in Sections II, III, and IV are proposed. I hope, albeit probably in vain, to be proven *wrong*! Only *experiments* can decide the issue for sure: *Experiments* are the final arbiter!

In Section VI, concluding remarks are provided describing implications *if* the Second Law could be violated *by any means whatsoever* [supradegeneracy, anti-supradegeneracy (whether strong or not), and/or otherwise].

II. DESCRIPTION AND DISCUSSION OF OUR SYSTEM

We now describe our simple system manifesting supradegeneracy (and/or *strong anti*-supradegeneracy, as will be discussed in Sections IV and V). Our system consists of a single particle of mass m confined within a closed hollow tube of *constant* internal diameter (and also constant external diameter). An illustration of the tube is shown in Figure 1. The particle could be an atom, molecule, Brownian particle, etc. It is maintained in thermodynamic equilibrium with a heat reservoir at temperature T via collisions with the interior surface of the tube, and is in a uniform gravitational field g (not to be confused with degeneracy G). It can be construed as a one-particle isothermal atmosphere. Generalization to a system containing n like particles (an n-particle isothermal atmosphere) is straightforward. (Of course, if $n > 1$, thermodynamic equilibrium is maintained via interparticle collisions as well as via collisions with the interior surface of the tube, interparticle collisions becoming more important with increasing n.)

The tube (see Figure 1) comprises three segments: Segment 0 is horizontal in its entirety at the datum altitude $z = 0$. Segment 1 is vertical at its join with Segment 0 at the datum altitude $z = 0$. At $z > 0$, Segment 1 curves away from the vertical at an angle $\theta(z)$ that increases monotonically with increasing z, but within the upper bound $\frac{\pi}{2}$ rad. The top of Segment 1, at which $\theta(z) = \theta(z_{\max}) < \frac{\pi}{2}$ rad, joins with the top of Segment 2, which is vertical in its entirety, at altitude $z_{\max}$. The bottom of Segment 2 vertically joins with Segment 0 at the datum altitude $z = 0$.

Thus the gravitational potential energy $E = mgz$ of our particle relative to the datum altitude $z = 0$ has as its minimum possible value $E_{\min} = 0$ and as its maximum possible value $E_{\max} = mgz_{\max}$. Hence in accordance with R1 and R2 the pertinent energy $E = mgz$ of our system is a *potential* energy (gravitational potential energy) associated with *one* degree of freedom (the vertical direction z).

Because the *entire* tube is of *constant* internal diameter, we avoid the impediments to cyclical motion of the particle owing to, for example, employing as Segment 1 a birch trumpet,[2] i.e., a cone flaring upwards: in particular, flaring upwards fast enough so that its horizontal cross-sectional area $A(z)$ increases with increasing z faster than the Boltzmann factor $e^{-E/kT} = e^{-mgz/kT}$ decreases with increasing z—flaring upwards such that $A(z) = A(z = 0)\,e^{NE/kT} = A(z = 0)\,e^{Nmgz/kT}$ $(N > 1)$: see, in Sheehan (2020b, the paragraph immediately following that containing figure 4 and note 3; 2020a).

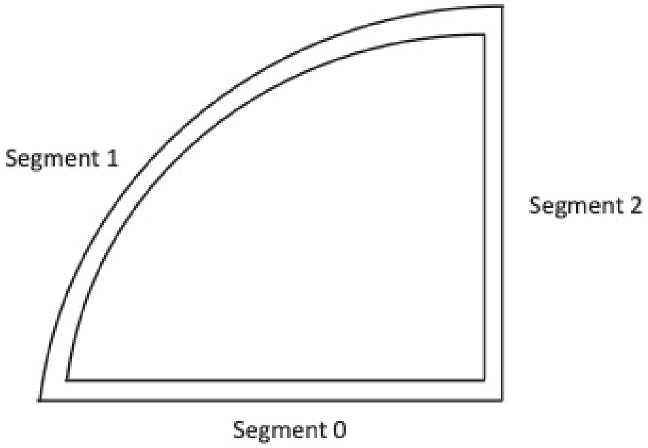

Figure 1. Illustration of the tube.

In Segment 0 and hence at the datum altitude $z = 0$, the probability of the particle being in a given tiny *length* interval dL of the tube is $P_{0,L}dL$. In both Segment 1 and Segment 2, the probability of the particle being in a given tiny *length* interval dL of the tube at altitude z is, in accordance with the law of isothermal atmospheres (Reif, 2009, sections 2.3 and 6.1–6.4, especially section 6.3 subsection "Molecule in an ideal gas in the presence of gravity"; Schroeder, 2000),

$$P_{1,L}(z)\,dL = P_{2,L}(z)\,dL = P_{0,L}e^{-mgz/kT}dL. \tag{4}$$

We note that the law of isothermal atmospheres (Reif, 2009, sections 2.3 and 6.1–6.4, especially section 6.3 subsection "Molecule in an ideal gas in the presence of gravity"; Schroeder, 2000, section 1.2, especially problem 1.16 and problem 3.37, chapter, especially sections 6.1, 6.2, and problem 6.14) is of course a special case of the Boltzmann (or canonical) distribution with $E = mgz$ (Schroeder, 2000, section 6.1, especially p. 223; Reif, 2009, section 6.2, especially p. 205; Kauzmann, 1967). (Of course, the terms "Boltzmann distribution" and "canonical distribution" are synonymous [Schroeder, 2000, section 6.1, especially p. 223; Reif, 2009, section 6.2, especially p. 205; Kauzmann, 2000]).

The terms "barometric equation" (Reif, 2009, section 6.2. especially p. 205) or "hydrostatic equation" (Reif, 2009, section 6.2. especially p. 205; Kauzmann, 2000; Schroeder, 2000, problem 1.16; Wark & Richards, 1999, section 1-5-4; Wallace & Hobbs, 2006; Holton & Hakim, 2013) are sometimes employed to denote hydrostatic equilibrium (Reif, 2009, section 6.2 especially p. 205; Kauzmann, 1967; Schroeder, 2000, problem 1.16; Wark & Richards, 1999, p. 11 and section 6-3-5; Wallace & Hobbs, 2006; Holton & Hakim, 2013), but not necessarily thermodynamic equilibrium (Reif, 2009, sections 2.3 and 6.1-6.4, in section 6.3 see especially subsection "Molecule in an ideal gas in the presence of gravity"; section 6.2 especially p. 205; Schroeder, 2000, section 1.2, especially problem 1.16, problem 3.37, chapter 6, especially sections 6.1 and 6.2 and problem 6.14); Kauzmann, 1967; Wark & Richards, p. 11 and section 6-3-5). Thermodynamic equilibrium necessarily implies hydrostatic equilibrium, but not necessarily vice versa. Thus *any* isothermal atmosphere is at thermodynamic equilibrium and hence necessarily also at hydrostatic equilibrium: This obtains in particular for a one-particle isothermal atmosphere in accordance with Equation (4). By contrast, Earth's atmosphere and oceans are almost always at hydrostatic equilibrium (or at least very nearly so) but not at thermodynamic equilibrium.

Also in accordance with the Boltzmann (or canonical) distribution (Schroeder, 2000, section 6.1 especially p. 223; Reif, 2009, section 6.2 especially p. 205; Kauzmann, 1967, sections 4.4, 4.5, 4.9) in Segment 1, the probability of the particle being in a given tiny *altitude* interval dz of the tube at altitude z is

$$\begin{aligned} P_{1,z}(z)\,dz &= P_{1,L}(z)\left(\frac{dL}{dz}\right)_1 dz \\ &= P_{0,L}\sec\left[\theta(z)\right]e^{-mgz/kT}dz. \end{aligned} \qquad (5)$$

Supradegeneracy obtains in Segment 1 because [within the restriction $\theta(z_{\max}) < \frac{\pi}{2}$ rad] we set

$$\begin{aligned} &\sec\left[\theta(z)\right] = e^{Nmgz/kT} \ \ (N > 1) \\ &\implies P_{1,z}(z)\,dz = e^{(N-1)mgz/kT} \ \ (N > 1)\,. \end{aligned} \qquad (6)$$

Because Segment 2 is vertical in its entirety, in Segment 2 the probability of the particle being in a given tiny *altitude* interval *dz* of the tube at altitude *z* is the same as of it being in a given tiny *length* interval *dL*, i.e., in accordance with the law of isothermal atmospheres (Reif, 2009, sections 2.3 and 6.1–6.4, in section 6.3 see especially subsection "Molecule in an ideal gas in the presence of gravity"; Schroeder, 2000, section 1.2 especially problem 1.16, problem 3.37, chapter 6 especially 6.1 and 6.2 and problem 6.14),

$$\begin{aligned} P_{2,z}(z)\,dz = P_{2,L}(z)\left(\frac{dL}{dz}\right)_2 dz = \left[P_{2,L}(z)\times 1\right]dz \\ = P_{2,L}(z)\,dL = P_{0,L}e^{-mgz/kT}dz. \end{aligned} \qquad (7)$$

Degeneracy *G* (*z*) corresponding to any given tiny *altitude* interval $z - \frac{1}{2}dz \le z \le z + \frac{1}{2}dz$ is proportional to the *length dL* of tube in this tiny *altitude* interval *dz*, i.e.,

$$G(z) \propto dL(z) = \frac{dL(z)}{dz}dz = \sec\left[\theta(z)\right]dz. \qquad (8)$$

At altitude *z* in Segment 1,

$$G_1(z) = G_1(z=0)\sec\left[\theta(z)\right] = G_1(z=0)\,e^{Nmgz/kT} \ \ (N > 1) \qquad (9)$$

By contrast, in Segment 2,

$$G_2(z) = G_2(z=0) = G_1(z=0) = \text{ constant.} \qquad (10)$$

Thus: (i) By Equations (5), (6), (8), and (9), $P_{1,z}(z)$ *increases* with increasing *z*—supradegeneracy (Sheehan, & Schulman 2019; Sheehan 2019, 2020a, 2020b, 2001–2022, 2018–2022)! But by Equations (4), (7), and (10), $P_{2,z}$ (*z*) *decreases* with increasing *z* in accordance with the law of isothermal atmospheres [Equation (3)]. But (ii) by Equations (4), (7), and (10), *both* $P_{1,L}$ *(z) and* $P_{2,L}$ *(z) decrease with increasing z at the same rate* as $P_{2,z}$ (*z*)—in accordance with the law of isothermal atmospheres [Equation (4)] (Reif, 2009, sections 2.3 and 6.1–6.4, section 6.3 see especially subsection "Molecule in an ideal gas in the presence of gravity"; Schroeder, 2000, section 1.2 especially problems 1.16 and 3.37, chapter 6, especially sections 6.1, 6.2, problem 6.14).

III. IMPLICATIONS PERTINENT TO THE SECOND LAW OF THERMODYNAMICS

Now the uppermost question pertinent to the Second Law of Thermodynamics is: Will the particle spontaneously circulate, manifesting spontaneous momentum flow (Zhang & Zhang, 1992)—flow that is both (i) sustaining and (ii) robust, i.e., capable of surviving disturbances and of restoring itself if it is destroyed (Zhang & Zhang, 1992)—either ascending in Segment 1, descending in Segment 2, and completing the (clockwise) circuit by returning to the bottom of Segment 1 via Segment 0—or in the opposite (counterclockwise) direction? It doesn't seem so. *Even though* $P_{1,z}$ *(z) increases* with increasing *z* as per Equations (5), (6), (8), and (9)—supradegeneracy (Sheehan, & Schulman, 2019; Sheehan 2019, 2020a, 2020b, 2001–2022, 2018–2022)! —and $P_{2,z}$ (*z*) *decreases* with increasing *z* in accordance with the law of isothermal atmospheres [Equation (4)] as per Equations (4), (7), and (10) (Reif, 2009, sections 2.3 and 6.1–6.4, in section 6.3 see especially the subsection entitled "Molecule in an ideal gas in the presence of gravity"; Schroeder, 2000, section 1.2, especially problems 1.16 and 3.37, chapter 6, especially sections 6.1, 6.2, problem 6.14). And *even though* because the *entire* tube is of *constant* internal diameter, we avoid the impediments to cyclical motion of the particle owing to employing as Segment 1 a birch trumpet,[2] i.e., a cone flaring upwards such that its horizontal cross-sectional area *A* (*z*) increases with increasing *z* as $e^{Nmgz/kT}$ (*N* > 1): see Sheehan (2020b, the paragraph immediately following that containing figure 4, and note 3). And *even though* both R1 and R2 are *also* fulfilled. Because the particle, if allowed to move through a horizontal tube segment, Segment *H* (*z*), connecting Segments 1 and 2 at *any* altitude *z*, would tend to drift in the direction of increasing P_L (*z*)—*not* in the direction of increasing P_z (*z*): P_L (*z*)—*not* P_z (*z*)—is the driver. But, repeating Equation (4), at *any* altitude *z*,

$$P_{1,L}(z)\,dL = P_{2,L}(z)\,dL = P_0 e^{-mgz/kT}dL. \qquad (11)$$

Thus P_L (*z*) is *constant* within *any* such horizontal tube segment, Segment *H* (*z*), at *any* altitude *z*—and equal to $P_{1,L}(z) = P_{2,L}(z)$ at this altitude *z*. Hence if there is a horizontal tube segment, Segment *H*(*z*), connecting Segments 1 and 2 at *any* altitude *z*, the particle would be *equally likely* to drift either from Segment 1 to Segment 2 or vice versa: random Brownian motion. [Segment 0 is Segment *H* (*z* = 0). Even though $\theta(z_{\max}) < \frac{\pi}{2}$ rad at the top of Segment 1 *per se*, there must be at least a tiny horizontal region at its join with the top of Segment 2, at altitude z_{max}. Alternatively, we can construe a short horizontal tube segment, Segment H (z_{max}), connecting the tops of Segments 1 and 2 at altitude z_{max}.] Hence the particle's motion *anywhere* within our closed tube would be random Brownian motion: It would *not* spontaneously circulate: either ascending in Segment 1, descending in Segment 2, and completing the (clockwise) circuit by returning to the bottom of Segment 1 via Segment 0—or in the opposite (counterclockwise) direction. It would *not* manifest the spontaneous momentum flow (Zhang & Zhang, 1992) that would be required to challenge the Second Law.

It doesn't seem to matter whether there is only one particle in our tube—a one-particle isothermal atmosphere—or an isothermal atmosphere comprising two, three, or many particles. As per Equations (4) and (11), the smoothed-out long-time-average density of *one* particle as a function of altitude z in our tube corresponds to thermodynamic equilibrium (Reif, 2009, sections 2.3 and 6.1–6.4, in section 6.3 see especially the subsection entitled "Molecule in an ideal gas in the presence of gravity,", section 6.2 especially p. 205; Schroeder, 2000, problem 1.16; Kauzmann, 2000; Wark & Richards, 1999, p. 11 and section 6-3-5) and hence also to hydrostatic equilibrium (Reif, 2009, section 6.2; Kauzman, 1967; Schroeder 2000, problem 1.16; Wark & Richards, 1999, section 1-5-4; Wallace & Hobbs, 2006, section 3.2; Holton & Hakim, 2013, section 1.4.1).

Thus also the density of an isothermal atmosphere comprising two, three, or many such particles as a function of altitude z in our tube would correspond to thermodynamic equilibrium (Reif, 2009, sections 2.3 and 6.1–6.4, in section 6.3 see especially the subsection "Molecule in an ideal gas in the presence of gravity", section 6.2 especially p. 205; Schroeder, 2000, problem 1.16; Kauzmann, 2000; Wark & Richards, p. 11 and section 6-3-5) and hence also to hydrostatic equilibrium (Reif, 2009, section 6.2 especially p. 205; Kauzmann, 2000; Schroeder, 2000, problem 1.16; Wark & Richards, 1999, section 1-5-4; Wallace & Hobbs, 2006; Holton & Hakim, 2013).

Thus also the density of *any* isothermal fluid (gas or liquid) as a function of altitude z in our tube would correspond to thermodynamic equilibrium and hence also to hydrostatic equilibrium). If there is only one particle in our tube, thermalization occurs via collisions with the inner wall of the tube; if there are $n > 1$, via interparticle collisions as well as via collisions with the inner walls of the tube (interparticle collisions becoming more important with increasing n)—but this seems to make no difference. That is why spontaneous momentum flow (Zhang & Zhang, 1992) can*not* be manifested, irrespective of the nature or density of the fluid (gas or liquid) in our tube. (We re-emphasize that thermodynamic equilibrium necessarily implies hydrostatic equilibrium but not necessarily vice versa).

Thus, at least in our system, supradegeneracy apparently does *not* challenge the Second Law of Thermodynamics—*despite* both R1 and R2 *also* being fulfilled. But it seems to be an open question whether or not this negative result is similarly true for *all* systems manifesting supradegeneracy, especially given that analyses, including computer simulations but to the best knowledge of the author at the time of this writing not yet experimental tests, of other supradegenerate systems at least *prima facie* seem to yield positive results (Sheehan & Schulman, 2019; Sheehan, 2019, 2020a, 2020b, 2001–2022, 2018–2022). The crucial question seems to be: What is the *minimal complete set* of *additional* requirements R* (tentatively conjectured to include R1 and R2)—over and above supradegeneracy *per se*—that must be fulfilled by a supradegenerate system if it is to challenge the Second Law?

But *even if* our negative result *does* turn out to be similarly true for *all* systems manifesting supradegeneracy, such systems could still be useful *even within* the strictures of the Second Law (Sheehan & Schulman, 2019; Sheehan, 2019, 2020a, 2020b, 2001–2022, 2018–2022).

It is *important* to note that the negative result for the system that we consider does *not* depend on whether or not z_{max}, the altitude at the top of our system at the join of Segments 1 and 2, is high enough for suprathermality (Sheehan & Schulman, 2019; Sheehan, 2019, 2020a, 2020b, 2001–2002, 2018–2002), i.e., for $E_{max} = mgz_{max} \gg kT$ to obtain. That P_L (z) is *constant* within *any* horizontal tube segment, Segment H (z), at *any* altitude z and equal to $P_{l,L}(z) = P_{2,L}(z)$ at this altitude z—implies only random Brownian motion. And this implication is *in*dependent of the value of z_{max} and hence of $E_{max} = mgz_{max}$. Indeed, *even if* our particle *could* spontaneously circulate (Zhang & Zhang 1992) in challenge to the Second Law—according to our results it can*not*—this too would have been *in*dependent of the value of z_{max} and hence of $E_{max} = mgz_{max}$. [But if we wish for suprathermality to be obtained without requiring an inconveniently large z_{max} in Earth's gravitational field, see Sheehan (2020b, note 3), our particle should be massive, e.g., a Brownian particle rather than an atom or molecule of gas. If the Brownian particle is suspended in a fluid, then m should be construed as its *net* mass after subtracting the buoyant force provided by the fluid. The mass of a Brownian particle, or even its *net* mass if it is suspended in a fluid, can easily be large enough to avoid an inconveniently large z_{max} in Earth's gravitational field.] Thus the operation of supradegenerate systems in general, and in particular whether any such systems turn out to challenge the Second Law or all such systems operate within the strictures of the Second Law, does not *in principle* depend on whether or not suprathermality obtains—even if *in practice* suprathermality facilitates more efficient operation, whether in challenge to the Second Law or within its strictures (Sheehan & Schulman 2019; Sheehan 2019, 2020a, 2020b, 2001–2022, 2018–2022).

IV. ANTI-SUPRADEGENERACY

To recapitulate, we dub as *anti*-supradegeneracy $G(E)$ *de*creasing with increasing E and hence $P(E)$ decreasing with increasing E *faster* than the Boltzmann factor $e^{-E/kT}$. And we dub as *strong* anti-supradegeneracy $G(E)$ *de*creasing with increasing E *faster* than the Boltzmann factor $e^{-E/kT}$ and hence $P(E)$ decreasing with increasing E *faster* than the Boltzmann factor $e^{-E/kT}$ *squared*, i.e., faster than $e^{-2E/kT}$. In our system $E = mgz$ so we can, equivalently, employ $G(z)$ and$P (z) = e^{-mgz/kT}$.

Consider the system shown in Figure 1 *inverted*, i.e., *upside down*. In the inverted Segment 1, $G(z)$ not merely *de*creases with increasing z but does so *faster* than the Boltzmann factor $e^{-mgz/kT}$, and hence $P_{l,z}(z)$ decreases with increasing z not merely faster than the Boltzmann factor $e^{-mgz/kT}$ but faster than the Boltzmann factor $e^{-mgz/kT}$ *squared*, i.e., *faster* than $e^{-2mgz/kT}$: not merely anti-supradegeneracy but *strong* anti-supradegeneracy. Or consider a tube comprising an upright Segment 1 as shown in Figure 1 *and* an inverted Segment 1. Then *both* (i) $P_{l,z}(z)$ *in*creases with increasing z in the upright Segment 1: supradegeneracy! *and* (ii) $P_{l,z}(z)$ *de*creases with increasing z *faster* than $e^{-2mgz/kT}$ in the inverted Segment 1: *strong* anti-supradegeneracy! Yet exploiting *either* supradegeneracy *or* anti-supradegeneracy (even as in our system *strong* anti-supradegeneracy)—or even exploiting *both* supradegeneracy *and* anti-supradegeneracy (even as in our system *strong* anti-supradegeneracy)—does *not* seem to contravene compliance with the Second Law. Because, still, irrespective of $P_{l,z}(z)$, whether employing an upright Segment 1, an inverted Segment 1, or even *both* an upright Segment 1 *and* an inverted Segment 1, $P_{l,L}(z)$—*not* $P_{l,z}(z)$—is the driver. And $P_{l,L}(z)$ still—in *all* cases—decreases with increasing z *exactly* as the Boltzmann factor e–$^{mgz/kT}$ as per the law of atmospheres [Equation (4)] (Reif, 2009, sections 2.3 and 6.1–6.4, section 6.3, especially the subsection “Molecule in an ideal gas in the presence of gravity”; Schroeder, 2000, section 1.2, especially problem 1.16, problem 3.37, chapter 6, especially sections 6.1 and 6.2 and problem 6.14). Thus our result of Section III—that our particle would execute only random Brownian motion—*not* (either clockwise or counterclockwise) spontaneous momentum flow (Zhang & Zhang, 1992)—remains *un*changed.

We note that the concepts of supradegeneracy and anti-supradegeneracy (albeit without being dubbed with these names) have been considered previously (Denur, 2012). It was shown that the average fluctuating energy $\langle E \rangle$ above the ground state of a single particle confined to a single classical degree of freedom in thermodynamic equilibrium with a heat reservoir at temperature T can be much larger or much smaller than kT (Denur, 2012). But the larger $\langle E \rangle$ is, the more spatially delocalized the particle must be (Denur, 2012), and thus the greater the thermodynamic cost of overcoming its delocalization (Denur, 2012). Hence these previous considerations (Denur, 2012) were compliant with the Second Law (Denur, 2012).

V. SIMPLE EXPERIMENTAL TESTS OF OUR SYSTEM

It would be easy enough to bend a piece of transparent glass or plastic tubing into the shape described in the first four paragraphs of Section II and shown in Figure 1. And it would be equally easy to invert it—or to bend a piece of transparent glass or plastic tubing into an upright-plus-inverted Segment 1—as described in Section IV. An isothermal atmosphere consisting of a single Brownian particle, or of any number n of them, could be placed in the tube. *Both* isothermality (and hence thermodynamic equilibrium) *and* observability of the Brownian particle(s) could be ensured by *uniform* illumination of the *entire* tube. It would then be a simple matter to observe whether (a) the Brownian particle(s) spontaneously circulate (either clockwise or counterclockwise) (Zhang & Zhang, 1992), manifesting spontaneous momentum flow (Zhang & Zhang 1992), which is *not* compliant with the Second Law, or (b) whether they manifest only random Brownian motion, which *is*. I hope for (a), but probably in vain: realistically, we expect the result to be (b). *Probably*, but as of this writing *not certainly*, in vain: Only *experiments* can decide the issue for sure! *Experiments* are the final arbiter!

VI. CONCLUDING REMARKS: IMPLICATIONS *IF* THE SECOND LAW IS VIOLATED

As has been stated by Sheehan (2018, 2020b, 2022), *if* the Second Law of Thermodynamics could be violated—*by any means whatsoever* [supradegeneracy, anti-supradegeneracy (whether strong or not), and/or otherwise]—the implications would be revolutionary (Sheehan, 2018, 2020b, 2022)—indeed, more than revolutionary (Sheehan, 2018, 2020b, 2022).

All current energy sources and technologies—not only nonrenewable ones but also renewable ones (except photosynthesis)—could be rendered obsolete overnight (Sheehan, 2018, 2020b, 2022). Even so-called “renewable” current energy sources require continual *free*-energy (exergy) input paid for by the temperature difference between the hot solar photosphere and the cold depths of space. Also, even so-called "renewable" current energy sources, both directly via sunlight and indirectly via wind, rivers, ocean currents, waves, ocean thermal energy conversion (with a few exceptions, e.g., OTEC[3]) require expensive storage systems (Sheehan 2018, 2020b, 2022). Moreover, even so-called "renewable" current energy sources (including OTEC[3]) have environmental impacts, including the environmental impacts pertaining to disposal of worn-out materials and equipment: Reversing the degradation of worn-out materials and equipment may be entropically impracticable. By contrast, Second-Law violators require *zero* input, because *the same heat can be recycled, used over and over again, forever*—with no storage systems required (Sheehan, 2018, 2020b, 2022). With rare exceptions such as the launching of spacecraft and construction (e.g., of buildings, bridges, etc.), work is frictionally degraded to heat on short timescales, indeed, most usually, continually. If the Second Law is violated, wherever and whenever work is frictionally degraded to heat, *the same heat can be recycled back to work, used over and over again, forever*—with no storage systems required. *A fixed, finite quantity of heat can thus do an infinite amount of work!* Some of this work could be employed to reverse the degradation of worn-out materials and equipment—hence no disposal required either (Sheehan, 2018, 2020b, 2022). And it has been stated that systems violating the Second Law are approaching commercialization (Sheehan, 2018, 2020b, 2022).

But, that being said, we should also note that: "If the second law should be shown to be violable, it would nonetheless remain valid for the vast majority of natural and technological processes" (Cápek & Sheehan, 2005).

ACKNOWLEDGMENTS

I am very grateful to Dr. Daniel P. Sheehan for very helpful, insightful, and informative discussions and communications concerning supradegeneracy, and for his recognition of my contributions, especially in the first paragraph of the section entitled "Epicatalysis" and in the paragraph immediately following that containing figure 4 in Sheehan (2020b). I am also very grateful to two anonymous reviewers for very thoughtful comments and suggestions, to Dr. Daniel P. Sheehan and to Dr. George Hathaway, Guest Editors of this Special Issue of the *Journal of Scientific Exploration*, for their help with this paper, and to an anonymous computer artist contacted by Dr. Daniel P. Sheehan for converting my hand-drawn Figure 1 into the high-quality computer-art Figure 1 (one of the two anonymous reviewers suggested adding a figure). I am indebted to Dr. Donald H. Kobe, Dr. Paolo Grigolini, Dr. Daniel P. Sheehan, Dr. Alexey V. Nikulov, Dr. Bruce N. Miller, Dr. George S. Levy, Dr. Kent Mayhew, Dr. Bruno J. Zwolinski, Dr. Marlan O. Scully, Dr. Bright Lowry, Dr. James H. Cooke, Dr. G. R. Somayajulu, Dr. Wolfgang Rindler, Dr. Russel Larsen, Dr. Abraham Clearfield, Dr. Nolan Massey, Dr. Richard McFee, Dr. A. N. Grigorenko, and Dr. Thomas (Tom) Eugene Bearden for many lectures, discussions, and/or communications that greatly helped my understanding of thermodynamics and statistical mechanics. I thank Dr. Stan Czamanski and Dr. S. Mort Zimmerman for very interesting general scientific discussions over many years. I also thank Dan Zimmerman, Dr. Kurt W. Hess, and Robert H. Shelton for very interesting general scientific discussions at times. Additionally, I thank Robert H. Shelton for very helpful advice concerning diction.

NOTES

[1] Strictly, relativistic gravitational equilibrium vertical temperature gradients should be accounted for: See Garrod (1995, exercises 7.29 and 7.30) and Tolman (1987). At thermodynamic equilibrium, temperature increases downwards in any gravitational field. But these vertical temperature gradients are utterly negligible for the system that we discuss and for all systems discussed in the cited references. Moreover, the gravitational redshift reduces the temperature of heat radiated from a hot reservoir at a lower altitude to the temperature of a cold reservoir at a higher altitude by the time this heat reaches the higher altitude of the cold reservoir. Thus what the gravitational temperature gradient giveth, the gravitational redshift taketh away. So the Carnot efficiency is *zero*. Hence relativistic gravitational equilibrium vertical temperature gradients can-*not* be exploited to challenge the Second Law of Thermodynamics.

[2] Birch trumpet. https://en.wikipedia.org/wiki/Birch_trumpet

[3] Ocean thermal energy conversion. https://en.wikipedia.org/wiki/Ocean_thermal_energy_conversion

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Journal of
Scientific
Exploration

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Science

RESEARCH ARTICLE

Beyond the Thermodynamic Limit: Template for Second Law Violators

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SUBMITTED April 24, 2022
ACCEPTED August 6, 2022
PUBLISHED October 22, 2022

https://doi.org/10.31275/20222593

HIGHLIGHTS

Several of the most promising second law challenges currently in the literature follow a standard physical template; an exemplar is discussed.

ABSTRACT

For 150 years the second law of thermodynamics has been considered inviolable by the general scientific community; however, over the last three decades its absolute status has been challenged by dozens of theoretical and experimental counterexamples. This study explores commonalities between some of the most potent of these and reveals a common template that involves broken physical–thermodynamic symmetries and reservoirs of work-exploitable thermal energy stored at system boundaries. Commercially successful second law devices could disrupt the current energy economy and help support a sustainable energy future. This article expands on a talk presented at *Advanced Energy Concepts Challenging the Second Law of Thermodynamics*, a symposium hosted as part of the 4th *Annual Advanced Propulsion and Energy Workshop* (22 January 2022).

KEYWORDS

Second law of thermodynamics, Maxwell's demon, sustainable energy

I. INTRODUCTION

Among the principles of Nature, perhaps none is more consequential and intimately tied to the human condition than the second law of thermodynamics (Čápek & Sheehan, 2005). It guides almost every natural process from the size of nuclei up to the scale of the cosmos. It began with the Big Bang and will likely help decide the ultimate fate of the universe. The second law is believed to largely underwrite the very passage of time.

The second law conditions virtually everything we do. We are born, live (too briefly), and die by it. It weighs on our psyches as we grapple with disorder around us, endure the decay of all things, toil against the dissipation of our efforts, finally succumb to ageing, and are reduced to dust. It's been called a neurosis of Western Civilization (Čápek & Sheehan, 2005). The second law is, arguably, the most depressing of all physical laws. For these reasons and more, it has been called *the supreme law of nature* (Eddington, 1929).

Despite its downsides, the second law is essential to our existence. It mediates the mixing of chemicals in our bodies and the completion of biochemical reactions; its molecular chaos keeps us warm and contributes to the oblivion that allows the world (and us) to forget so that new things can arise. As Picasso said, "Every act of creation is first an act of destruction." The second law seems destructive, but it is essential to creation for that reason.

One of its most ringing endorsements is the following (Einstein, 1970): "[Classical] thermodynamics is the only physical theory of universal content concerning which I am convinced that, *within the framework of applicability of its basic concepts*, it will never by overthrown [emphasis added].

While this statement is regularly offered for the centrality of thermodynamics and the inviolability of the second law, in fact, its italicised clause renders Einstein's endorsement a tautology: *Thermodynamics is correct when it's correct*. It follows, then, that *thermodynamics (and the second law) is not correct when it's not correct*. This paper concerns this thesis.

II. A LITTLE THERMODYNAMICS

A. Thermodynamic Law

But what is this *second law of thermodynamics*? To begin, *thermodynamics* is the field of science concerned with the interplay between *work* and *heat*, the two basic types of energy in the universe. *Work* is high-grade, organized energy, while *heat* is low-grade, disorganized energy. *Energy is the currency of change*—nothing can happen without it—therefore, thermodynamics is central not just to physics, engineering, biology, chemistry, but to economics, industry, geopolitics, and every sphere of human activity. If *energy makes the world go 'round*, then the second law is its lord and master.

Thermodynamics is governed by four laws, designated 0, 1, 2, and 3. The zeroth and third laws are almost throwaways; they cover ways to define equilibrium and entropy, respectively. Both could be abolished and most scientists and engineers would neither care nor notice. Not so for the first and second laws: they are respected like nitroglycerin. They are the flesh and bone of thermodynamics.

The first law, conservation of energy, stipulates that the total mass–energy content of a closed system cannot change. Various forms of energy can interconvert—e.g., radiative, rest mass, chemical, gravitational, kinetic, thermal—but the total sum cannot change; in other words, there's no free lunch and you don't get anything for nothing. While this all seems quite fair and physically reasonable and, thus, worthy of a law of nature, in fact, the first law should not be considered a law at all, rather just a handy accounting scheme for energy. In a practical sense, this 'law' cannot be violated because if an apparent violation (loophole) were to appear—that is, some new type of energy were to be discovered that unbalanced the books—well then, *the books can be cooked*. In other words, it is always possible to invent a new form of energy to cover up any discrepancy, close any loophole, and null out any suspected violation to preserve the first law as inviolate.[1] As such, the first law violates Karl Popper's Principle of Falsification, which asserts that for a physical theory (or law) to be legitimate, it must be able to be tested and potentially be proven false. The first law does not satisfy this criterion, therefore, if it is a law, it is a peculiar one. Not so with the second law. If a violation of it is found, the law cannot be easily rejiggered to remain inviolate. In principle, it can be falsified and in recent years it has been.

There are a number of misconceptions concerning the second law, two of the most common of which are that: i) it cannot be violated, even in principle; and ii) it has been theoretically proven. Both spring from epistemological errors. *Physical laws are scientific postulates (axioms), and postulates by definition cannot be proven; they are either accepted or not accepted.* (Think, for instance, of the five postulates in Euclidean geometry.) Physical laws are statements about nature that are assumed to be true because they have been always observed to be so. However, one can never test a law in every possible physical scenario, therefore, one must always leave open the possibility that a counterexample might turn up. Its status, thus, is *contingent* and subject to Popperian falsifiability. Even a single violation is significant, for although it does not invalidate the law under circumstances where it does apply it vanquishes the law's absolute status, perhaps making it a subcase of a more general law.

Misconception (ii)—the second law can be rigorously derived (theoretically proven)—is also an epistemological error. The second law is an axiom, not a theorem. Were it theoretically provable, it would be a mere theorem, reliant on deeper axioms for its support. 'Proving' the second law would also violate Popper's falsifiability principle.

These misconceptions have multiple causes, some defensible, others less so. Certainly, the second law rings true, validating by our experience of the world that disorder tends to increase. Furthermore, its statement is simple, snappy, easy to use and comprehend. These misconceptions can also be traced in part to the tendency of physicists to hang their beliefs on idealized models, what T. S. Kuhn has called *exemplars*. One of the most seductive is the ideal gas: a collection of non-interacting point masses with kinetic (thermal) energy. This model provides wonderful insights and good physical approximations into the behaviors of many real gases. Equally seductive, it can be derived simply and exactly. Capping it off, it provides an ideal test case for the second law, one that can proven rigorously, which it passes summa cum thermodynamically. From there, it seems intuitive to extrapolate this theoretical triumph for an ideal gas to real gases and from there on to every other thermodynamic system in the universe.

It is the experience of this author that a plurality of physicists turn to the ideal gas both for intuition and justification for the second law's behavior and absolute status. Unfortunately, the universe is neither simple nor ideal. As Mark Twain noted, *What gets us into trouble is not what we don't know. It's what we know for sure that just ain't so*. This tendency to extrapolate from simple, idealized cases to more complex ones, even though lacking sufficient justification, will be called the *Ideal Gas Syndrome* (IGS). When it comes to the second law, the IGS courts trouble in spades.

B. The Second Law

If the first law of thermodynamics is not a real law and the zeroth and third are ignorable, then one might say that thermodynamics really has only one significant law: the second. Fortunately, what it lacks in number, it makes up for in formulations. There are more than a dozen standard ways to state the second law, all of which are more than a century old and most of which were developed in the 19th century, during the age of steam engines. Here we will focus on two of the most prominent and useful.

The *Kelvin–Planck* formulation is considered by many to be the gold standard: *It is impossible to convert a quantity of heat solely into work in a thermodynamic cycle*.[2] The second law embodies one of the starkest asymmetries in Nature. Work can be turned wholly into heat, but the reverse is not possible. That is, heat cannot be turned back wholly into work in a thermodynamic cycle. As a demonstration, rub your hands together. They warm up. Now rub them in reverse. They just warm up more. The heat in your hands contains the energy of the work you did rubbing them, but you'll not get it back as motion of your hands. (The same thing happens to almost all the energy you will ever use, it will end up as unrecoverable heat in the environment.)

Heat generation can be viewed as a physical tax paid by every working system, a form of energy that can never be fully redeemed back into work. The original energy (in the form of work) isn't lost—the first law guarantees this—but it is reduced to a less usable, less effective form: heat. On the everyday level this means that useful (work) energy (e.g., electricity, carbon fuels, solar, wind, or nuclear) must be constantly supplied to offset losses from heat generation. Taxes are higher is some places than in others. For an electric heater the tax is high and immediate, which is a good thing for staying warm, while for a sleek electric car the tax is deferred long enough for efficient transportation. In the end, however, for both cases the tax paid is almost always 100 percent.

The second formulation of the law, the *Planck* form, reflects a view of thermodynamics incorporating entropy and statistical mechanics: *For any spontaneous process, the entropy change of the universe is never negative.* If entropy is taken to be a measure of disorder, then the Planck formulation says that for anything that happens (a spontaneous process) the overall disorder of the world must increase or remain the same, but it will never decrease. This validates what we understand intuitively and viscerally: messes never clean themselves up and, left to their own devices, systems tend to become more disorganized. When it comes to holding back entropy generation, the best one can hope for is accomplished by doing nothing at all because every act of cleaning up, though it might reduce entropy (disorder) locally, must increase the overall entropy of the universe. If you're really intent on not messing up the universe, kill yourself, and you won't generate entropy through your biochemical reactions and other life activities.

In sum, the second law is a thermodynamic ratchet system that inexorably degrades high quality energy (work) into lower quality energy (heat), reducing order to disorder, marking our time as it *creeps in this petty pace from day to day to the last syllable of recorded time . . . pointing the way to dusty death* (Shakespeare). Let us now turn to some approximations and oversights that have contributed to this thermodynamic fatalism and set the stage for the law's overthrow.

C. Boundaries and the Thermodynamic Limit

Like any well-developed field, thermodynamics is replete with technical terms and approximations that embody its viewpoint and ethos. Among the most widely applied is the *thermodynamic limit*. This idea and handy approximation streamlines analysis and leverages intuition, but, sadly, it is also a mindset and a classic case of the IGS, which appears to have blinded the scientific community to the limits of the second law for at least a century.

As a technical term, the thermodynamic limit refers to an approximation in which the number of particles (atoms/molecules) in a system (N) is taken mathematically to go to infinity ($N \rightarrow \infty$), while at the same time the volume of the system (V) is also taken to go to infinity ($V \rightarrow \infty$) in such a way that their ratio, the number density ($n = N/V$) remains finite. This handy approximation streamlines calculations of bulk thermodynamically quantities—e.g., specific heat, various free energies, thermal diffusivity, pressure, latent heats of vaporization and fusion—without having to deal with often unwanted, complex, or physically intractable implications of boundary surfaces.

The utility of the thermodynamic limit is unquestioned, but it has led to a general mindset within much of the scientific community that, somehow, boundaries and surfaces have limited thermodynamic significance, that they can be ignored with perhaps only minor consequence or even with impunity. Few beliefs could be further from the truth and few assumptions have greater consequence.

In fact, boundaries are essential to physical reality. They define the physical world, allowing us to differentiate one object or region from another. When we interact with the world, it is usually through boundary surfaces: the ground we stand on; the surface of a table; the printed word on a page; the colorful skins of fruits. Without them, the universe would be an undifferentiated blur.

Thermodynamically, *boundaries are where the action is* because most physical interactions occur there. Entire fields of study are defined by them. At the boundary of a plasma, for example, is a *Debye sheath*, where the electron and ion energies are anomalously high, where temperature is not well defined, and strong electric fields are found. At equilibrium, the electrostatic potential of an entire plasma can be determined by its boundary. Transistors, diodes, LEDs, and other semiconductor technology depend on the intricate physics at the microscopically thin boundaries between n- and p-doped semiconductors that make them up. Heterogeneous catalysis, which is the beating heart of industrial chemistry and which touches 90% or more of all manufactured products in some way, is defined by surface reactions. And, of course, living cells and their organelles are bounded by membranes that regulate the influx and efflux of chemicals and ions necessary for life. (Roughly half the total metabolic energy of a typical cell is devoted to membrane processes.) Indeed, boundaries are ignored at one's peril.[3]

For our purposes, boundaries represent broken physical or chemical symmetries in a system, discontinuities in chemical potential, pressure, or temperature, any one of which can, in principle, be tapped to perform work. As such, boundaries represent reservoirs of free energy. So long as there are surfaces, the universe cannot be at full thermodynamic equilibrium and there will always be something left to happen. Under certain circumstances, this boundary energy can be tapped cyclically for work. If it is derived from ambient, single-temperature thermal energy, the system might violate the second law.

D. Second Law Renaissance

Over the last 25–30 years there has been a renaissance in investigations of potential violations of the second law (Cápek & Sheehan, 2005). It began quietly in the 1980s with theoretical proposals by Lyndsay Gordon and Jack Denur. By the mid-1990s, several university research teams had picked up the scent and began nipping at the second law's heels. By the early 2000s the interest had grown sufficiently to motivate several international conferences devoted to the challenges to the law (Sheehan, 2002, 2007, 2011). The first scientific monograph on the subject was published in 2005 (Cápek & Sheehan, 2005). For the next 10 years theoretical proposals continued to mount and were soon joined by experiments that increasingly demonstrated deficiencies in the law. Now, in the early 2020s intellectual property is being amassed in anticipation of commercializable *second law devices* (SLD). In total, over the last 30 years more than four dozen second law challenges have advanced into the mainstream scientific literature, more than the total over the previous 150 years combined. The latest challenges are experimentally testable, some potentially commercializable.

The span of physical regimes encompassed by the various challenges is bracing. In size they range over at least 14 orders of magnitude, from the dimension of cell membranes (0.1 microns) up to that of compact planetary systems (10,000 kilometers); in mass they span 42 orders of magnitude. Operating temperatures range from just above absolute zero up to several thousand degrees, the melting points of ceramics and refractory metals. All four standard phases of matter are represented (solid, liquid, gas, and plasma), as are both classical and quantum regimes.

E. Maxwell's Demon

One of the most unfortunate diversions in the 170-year history of the second law has been the preoccupation with Maxwell's demon (Leff & Rex, 1990, 2002). The demon is an imaginary *heat fairy*, a theoretical microscopic creature who, by sharp observation and quick action, is able to sort molecules on an individual basis so as to create temperature or pressure differences that can be used to perform work, thereby subverting the second law.

In Figure 1, Maxwell's demon is imagined as a microscopic version of the mischievous Calvin (from the cartoon *Calvin and Hobbes*) who operates a trap door in a box of molecules. By opening the door at precisely the right moments, Calvin can preferentially direct molecules into one side of the box rather than the other. Eventually, molecules accumulate on one side and a pressure difference builds up between the two sides of the partition. This is then harnessed to do pressure-volume work, much like as is done in an automobile engine. Once the work is completed and the pressure difference is exhausted, Calvin starts over and separates the molecules again. If this scheme actually worked, it would constitute a second law violator. Regret-

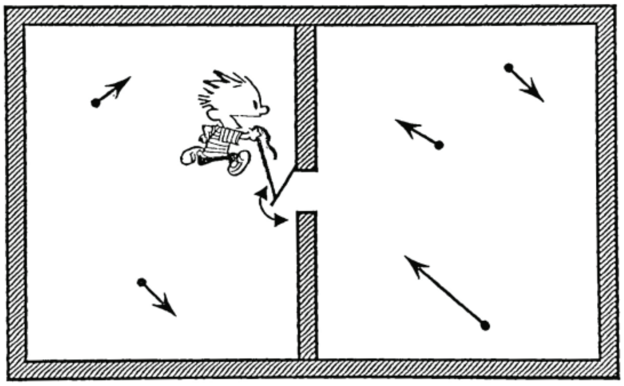

Figure 1. Maxwell's demon imagined as that lil' devil, Calvin.

tably, like all purported SLDs thus far that rely on manipulating molecules on an individual basis or that attempt to exploit their natural fluctuations, the Calvin demon fails—as do most of Calvin's schemes in the comics.

Maxwell's demon's shortcomings are so numerous that it's remarkable that so much ink has been spilt over them. The demon is microscopic and, even after more than 150 years of discussion, it remains unknown how it could be constructed. A sighted demon is rendered effectively blind because in a blackbody cavity everything has the same color, thus, it could not discriminate between the radiation emitted by the walls, the atoms it's trying to sort, and the radiation output of its own eyes. Its microscopic fingers would shake uncontrollably, just like the molecules it attempts to handle, so sorting molecules would be nearly impossible. Its final fatal flaw, however, comes from thinking too much. In order to complete a full thermodynamic cycle, the demon must forget what it knows about the molecules it sorts, in other words, it must clear its memory banks. However, information theory has shown that this forgetting automatically creates enough entropy to offset any work (or entropy decrease) that it may have done. In all, it appears that Maxwell's demon was, is, and probably always will be a straw man. And yet, this hasn't diminished the scientific community's fixation with it. Perhaps the community should pick on someone more its own size, rather than on a hapless, hopeless theoretical construct from the 19th century. Enter the Maxwell zombie (Sheehan, 2018).

II. TEMPLATE FOR SECOND LAW CHALLENGES

Many of the most promising and potent second law devices (SLD) have been found to share a common template (Lee, 2021; Thibado et al., 2020; D'Abramo, 2012; Moddel et al., 2021; Sheehan et al., 2022; Sheehan, 2022; Sheehan & Means, 1998, Sheehan et al., 2005; Sheehan et al., 2014). Several were discussed at the symposium upon which this special issue is based.[4] The template consists of the following four physical conditions.[5]

1) Physical/Thermodynamic Asymmetry at Boundaries: *The system's physical boundaries have strong thermodynamic activity or properties. In particular, they have one or more physical and/or thermodynamic asymmetries built into them that create a discontinuity in chemical potential, temperature or pressures in the system.*

Every surface is thermodynamically active to some degree, but some are more active than others. For instance, liquid helium or a piece of room-temperature teflon is thermodynamically active but far less so than, say, an oxygen plasma or a slab of tungsten metal heated to 2000 K. Surfaces are notoriously complex entities—entire fields of physics and chemistry are devoted to them. By its very existence, a surface represents a discontinuity in chemical potential, which in principle might be used to do work, but how much, how well, and how fast must be determined on a case-by-case basis. For an SLD, its asymmetry must generate an asymmetry in some type of flux (e.g., electric current, gas particles, chemical species) that can convey or be converted into work (high quality, organized energy). Without this asymmetry, there can be no net directional flux, therefore, no capacity to conduct work. Note, the critical flux need not be generated at the location of the SLD asymmetry itself.

2) Thermal Energy Reservoir: *The asymmetry in 1) creates a macroscopic reservoir of thermally generated free energy at or near a boundary.*

The thermal energy of an individual molecule is minute and randomly oriented and, therefore, unsuitable for performing work. To be suitable, the energy must be macroscopic (forming a reservoir) and ordered. The thermodynamically active boundaries perform this role: They organize, amass, and direct the thermal energy of individual molecules. By analogy, an aimless mob might have the same number of persons as an army, but the army is the more structured entity and thus can be more effective for conducting organized operations. The system boundaries are the recruiters, the drill sergeants, and the generals who organize, mobilize, and direct the army of molecules such that they can perform work. Together, they might have no more total energy than they did as individuals, however, because they operate en masse, they can direct their thermal energy to perform macroscopic work—and perhaps break the second law.

The energy reservoir can consist of pressure, temperature, or chemical concentration differences, even electric or magnetic fields. Such reservoirs constitute a nonequilibrium state than can be harnessed to do work. In everyday circumstances, such energy reservoirs power the world. For instance, terrestrial temperature differences create atmospheric pressure differences, which in turn create the weather. Temperature differences between the Earth's mantle and crust drive plate tectonics; in the Sun they drive energy from the core to the surface, where it is radiated away as sunlight. Electric fields induce electric currents that make electronics possible. Concentration differences are part-and-parcel of living organisms, especially in and around membranes. Life is a decidedly *non-equilibrium* process.[6] Thermodynamically, life is one of the second law's best friends.

3) Independent ('Orthogonal') Work Extraction: *The*

system has a means by which to extract macroscopic work from this boundary energy reservoir. This energy extraction mechanism is independent of (i.e., operationally orthogonal) to the thermal energy collection mechanism.

Criteria (1) and (2) account for the accumulation of thermally derived energy into a potentially useful form, but by themselves they are not sufficient for an SLD.

There must also be a mechanism to harvest this energy as work. *Independent* and *operationally orthogonal* mean that the mechanism by which the thermal energy reservoir is tapped is distinct from the processes which created the reservoir in the first place. This precludes or reduces the possibility that the organized boundary energy will backslide into its original, random, thermal form. It decouples the energy storage and energy use processes. A later example will make this clearer.

4) Resettable Metastable Configuration: *Once macroscopic work has been extracted, the system spontaneously returns to its original physical/thermodynamic state via the absorption of heat from its surroundings.*

This step completes the thermodynamic work cycle. The original state of the system involves a macroscopic energy reservoir that has accumulated at boundaries due to the spontaneous thermodynamic rearrangement and marshalling of thermal energy. The extraction of work by the independent/operationally orthogonal process produces useful work, however, by the first law (conservation of energy), this must put the system into a lower energy state than it was before the work was extracted. This lower energy manifests itself as cooling of the system. Ironically, now that the system is cooler than its surroundings (recall that it starts off at the same temperature),[5] the Clausius form of the second law[7] guarantees that heat conducts from the surroundings into the system until it returns to its original thermodynamic equilibrium.

If the system successfully completes these four steps, it has completed a thermodynamic cycle in which heat has been converted solely into work, a cycle strictly forbidden by the Kelvin–Planck form of the second law. Several points are noteworthy.

First, the fact that the original equilibrium state of the system is able to produce work and, therefore, go into a lower energy state, implies that it is, in fact, a high-energy metastable state. The universe is replete with such metastable states—actually, it can persuasively be argued that *every* system in the universe is a metastable state of some sort because one can always find a way to reduce it to a higher entropy, lower energy configuration. However, only a select few systems can amass macroscopic energy stores by thermal means, fewer still are coupled to independent/orthogonal energy extraction subsystems, and even fewer are able to return to their original states by absorbing heat from their environments. Second law devices can.

Second, most of these four conditions are similar to those operating in everyday work-producing, second-law–abiding devices. Consider, for instance, a gasoline engine. It has boundaries and asymmetries built into it. The piston and cylinders have walls upon which high pressure gases (created by the ignition of the gasoline–oxygen mix) exert forces and produce net work when the piston moves smoothly and asymmetrically in one direction along the inside of its matching cylinder. Work is extracted by an 'independent/orthogonal' device: a mechanical crank that converts the pressure force into rotational motion that is eventually coupled to the wheels. And, once the piston returns to its original position in the cylinder, the system resets and the thermodynamic cycle repeats. And off you go!

In all, one sees shades of Criteria 1, 3, and 4 in everyday thermodynamic cycles. What distinguishes the SLDs from everyday work-producing systems is that their energy does not derive from external free energy sources (e.g., gasoline, wind, solar, fission), but rather, from ambient thermal energy, Criterion 2.

Third, the second law applies to virtually every multiparticle system in the universe—even to SLDs. For example, in Condition (4) the SLD cools when it performs work, but the Clausius form guarantees that it warms back up.[7] Nonetheless, for its full thermodynamic cycle the SLD violates the Kelvin–Planck form of the law. This ambivalence of the SLD toward the second law suggests that the various forms of the law might not be equivalent or that they are internally inconsistent (self-contradicting) in some circumstances.

III. THERMAL BATTERY

As a demonstration of these four criteria (§II), let's consider the *asymmetric membrane concentration cell* (AMCC), which for simplicity will be called the *thermal battery* (Sheehan et al., 2022; Sheehan, 2022). This device converts environmental heat into electricity using spatially asymmetric electrochemical diffusion.

A. A Taste for Chocolate

Electrochemistry is one of the most challenging scientific fields, drawing widely from physics, chemistry, and engineering (Newman & Thomas-Alyea, 2004; Bockris & Reddy, 2002; Hibbert, 1993). To understand the key thermodynamic processes driving the thermal battery, consider the following edible scenario. Imagine a long narrow corridor (length L, width w, Figure 2) with crowds of chocolate lovers (CL) milling about randomly, occasionally running into the corridor walls, and sometimes bumping into each other. No one speaks or communicates; everyone acts independently.[8] Along the walls are boxes of chocolates. They are arranged in a special way. On the left side of the corridor (Figure 2) the boxes are relatively scarce (widely spaced) and the chocolate is relatively lousy (e.g., Hershey's), but as one proceeds to the right, the quality of chocolate and the density of boxes steadily increase, such that at the far right side of the corridor it's wall-to-wall Läderach (better than Ferrero Rocher, Ghirardelli, Lindt, or Godiva). The rules about eating the chocolate are simple: (i) upon colliding with a wall, if a CL encounters a box, he must pick a piece of chocolate and consume it entirely, but if there is no box, he simply reflects and continues randomly walking about the corridor; (ii) the chocolate can only be eaten at the wall; (iii) the CL cannot leave a spot on the wall until he finishes the piece selected; (iv) a CL spends longer eating a piece of high quality chocolate than eating a low quality one; and (v) after consuming the piece and leaving, the CL must re-enter the corridor and resume wandering aimlessly about until colliding with another wall.

Given these rules, it's not hard to deduce that, over time the chocolate lovers will accumulate on the walls near the right side of the corridor (i.e., the solid phase of CLs) because, even if their wanderings are entirely random, there are more sites there with which to attach and they spend longer times at each site eating. This, however, counts only CLs attached to the corridor walls. If one instead considers where the most chocolate lovers are wandering around freely in the space within the corridor, between the walls (i.e., in the liquid phase of CLs), the opposite is true: They accumulate primarily on the left end of the corridor—after all, they aren't spending much time stuck to the wall eating.[9] This is depicted in Figure 2b. To be clear, the wall surface (linear) density of chocolate lovers (CL/m) is highest on the right side of the corridor (blue curve), but their liquid (areal) density (CL/m^2) is highest on the left side (red curve). The latter result can have consequences.

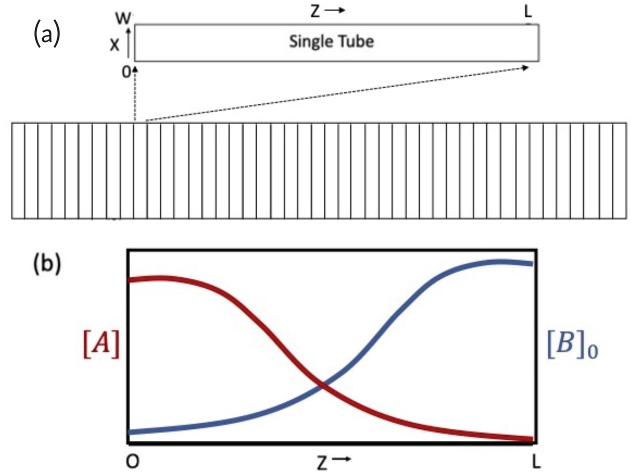

Figure 2. Depictions of thermal battery membrane, tube, and species concentration profiles in tube. **(a)** Membrane as array of microscopic tubes and magnified single tube extracted from the membrane. **(b)** Distribution of binding sites (or chocolate boxes), ($[B(z)]_0$ in blue) and resulting concentration of solute A (or chocolate lovers), ($[A(z)]$ in red) inside tube. Note inverse spatial relationship between $[A]$ and $[B]_0$.

Let's say that after the diffusion of CLs has leveled off and come to an equilibrium, a game of tug-of-war is arranged in which: (a) contestants are drawn exclusively from the liquid phase of chocolate lovers at the two ends of the corridor; and (b) the team that pulls the hardest wins a prize.[10] Because the left corridor has a higher liquid density of players, their end of the tugging rope has many more contestants than the right end of the rope and, as a result, they win the game.[11]

After the game of tug-of-war is concluded and the spoils divided, everyone is brought back to the middle of the corridor and the sorting begins again. This cycle of sorting, tugging, and winning repeats ad infinitum. This metaphorical scenario describes the essential features of the thermal battery.

B. Thermal Battery

The thermal battery consists of two subsystems: (1) the *asymmetric membrane separator* (AMS), which separates a solution of A into two distinct concentrations with concentration difference $\Delta[A] \equiv [A]_{high} - [A]_{low}$, thereby fulfilling Criteria (1, 2); and (2) the concentration cell (CC), which exploits the $\Delta[A]$ to generate electricity, thereby satisfying Criterion (3). It is depicted in Figure 3. The AMS consists of two thin liquid reservoirs separated by a chemically asymmetric membrane (Figure 2a). Here the membrane is modeled as an array of large aspect ratio microscopic tubes bundled together lengthwise and filled with species A dissolved in a solvent. Individual tubes are microscopic; typical dimensions are in the range: 10^{-6} m $\leq L \leq 10^{-4}$ m and 10^{-8} m $\leq w \leq 10^{-6}$ m. Billions or trillions of tubes comprise a single AMS membrane. They are modeled as straight and uniform. The tubes are identical, therefore to understand the physical chemistry of a single tube is to understand that of the entire membrane. The AMS membrane in Figure 3a is represented by such a single tube, as in Figure 2a.

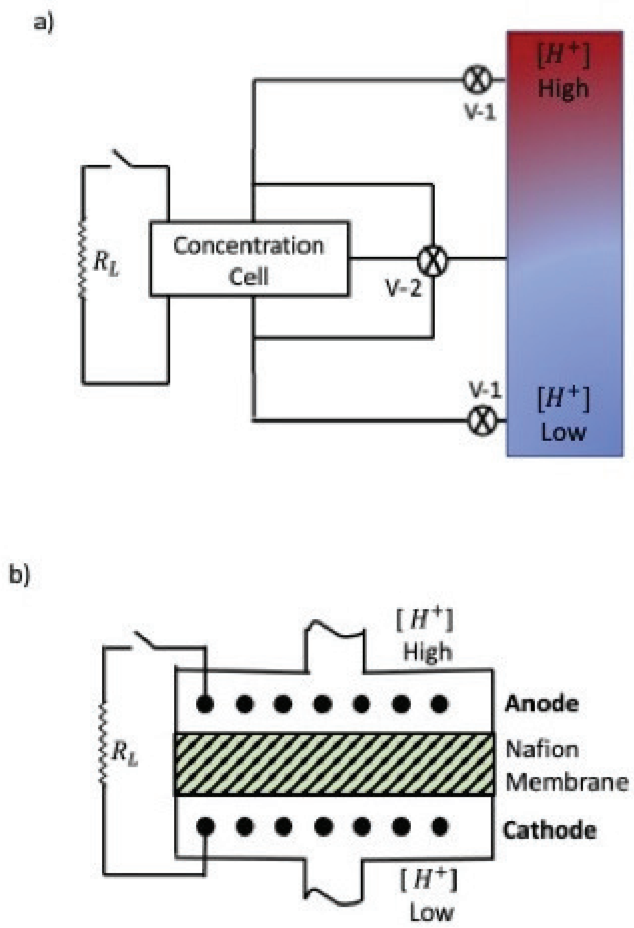

Figure 3. Schematic of thermal battery. **(a)** AMS with valves, plumbing, and concentration cell. **(b)** Concentration cell magnified. V-1 open/V-2 closed configuration admits solutions into concentration cell for electricity generation; V-1 closed/V-2 open configuration returns solutions to AMS for reseparation. Note: The AMS in this figure is a representation of the membrane tube in Figure 2a.

The solute molecules A randomly diffuse in the solvent, analogously to the aimless wanderings of the chocolate lovers, and temporarily attach to the binding sites on the tube wall (B), following in the simple chemical reaction:

$A + B \rightleftharpoons AB$,

for which the chemical equilibrium constant is:

$$K_{\mathrm{eq}} = \frac{[AB]}{[A][B]}. \qquad (1)$$

Here $[A]$, $[B]$ and $[AB]$ are the normalized volume and surface concentrations of species A, B, and AB.

It is shown elsewhere (Sheehan et al., 2022; Sheehan, 2022) that if $[B]$ and K_{eq} (a proxy for the A-B binding strength) are made to vary along the length of the tube, then $[A]$ will also vary. This is analogous to the variation of the quality of chocolate and number density of boxes in the chocolate tasting corridor (§III.A). The results for the two scenarios are similar, as depicted in Figure 2b. Because of the differential binding of A to B, at equilibrium there is a concentration gradient of A created across the width of the membrane. As with the chocolate example, this has consequences.

For laboratory experiments conducted at University of San Diego (USD), custom membranes were fabricated to separate hydrogen ions (H^+) in hydrochloric acid (HCl) into different concentrations. The $[H^+]$ gradient created a matching chloride ion (Cl^-) concentration gradient (in order to satisfy the requirement for electrostatic quasi-neutrality). The chloride ion concentration gradient was used to power a new type of electrochemical cell, the *asymmetric membrane concentration cell* (AMCC), the thermal battery depicted in Figure 3.

The concentration cell is non-controversial; it has been well understood and studied for a century or more (Newman & Thomas-Alyea, 2004; Bockris & Reddy, 2002; Hibbert, 1993). It is the AMS that renders the AMCC a second law device.

There are several types of electrochemical cell. Everyday batteries (e.g., dry cells, alkaline, lead-acid, Li ion rechargeables), also known as *voltaic cells*, rely on the transfer of electrons between *disparate* chemical species to generate electricity. A lesser-known type, the *concentration cell*, generates electricity using a single chemical species, but at two distinct concentrations, like those generated by the AMS. Ironically, the energy derived from the AMCC is due to the entropy of mixing the two distinct single-species concentrations—a classic application of the second law. In the USD experiments, the concentration cell was driven by the difference in the chloride concentration across the width of the membrane.

The electromotive force (voltage) generated by single concentration cells is usually small, typically 10–100 mV, however, they can be added in series. Because the AMS membranes and concentration cell electrodes can, in principle, be made micron-thin, in theory, a multi-volt AMCC can be made paper-thin. Their theoretical energy densities are sizable, though still 1–2 orders of magnitude less than those of standard voltaic cells. The reason for this is that the characteristic energy of indi vidual species in a thermal battery is of the order of a thermal energy unit, kT , where k is the Boltzmann constant (1.38×10^{-23}J/K) and T is the absolute temperature (Kelvin, K). In contrast, the energy associated with species in a traditional voltaic cell is that of a standard chemical reaction, on the order of 100 kT.

C. Thermal Battery and Template Criteria

Let's examine how the thermal battery meets the four criterion in §III.

Criterion 1: The heart of the AMCC is the AMS. As its name suggests, the AMS has a built-in chemical asymmetry with respect to the binding sites, B, both in terms of surface number density and binding strength. These two asymmetries generate a spatially reciprocal asymmetry in the solute concentration, $[A]$. In the USD experiments, the AMS binding sites were carboxylic (COO^-) and sulfonic (SO^-) moieties, while the solute species were the hydrogen ion (H^+) and chloride ion (Cl^-).

Criterion 2: The concentration difference across the AMS membrane ($\Delta[A] = \Delta[H^+]$) is derived from particle diffusion, hence from ambient thermal energy (kT). The $\Delta[A]$ in the AMS is a metastable equilibrium state of the solute. It is also a macroscopic reservoir of thermally generated free energy because it can be used to power a concentration cell. In the USD experiments, $\Delta[A] = \Delta[Cl^-]$.

Criterion 3: The free energy inherent in $\Delta[A]$ is extracted by the electrodes on opposite sides of the AMS (Figure 3a). These concentration cell reactions are 'orthogonal' and independent of the reactions in the AMS that created the original $\Delta[A]$. In the USD experiments, the AMS separates $[H^+]$ and the $[Cl^-]$ comes along for the ride. The concentration cell exploits the chloride ion concentration gradient using Ag/AgCl electrodes (Figure 3b).[12]

Criterion 4: The AMCC expends its $\Delta[A]$ to generate electricity. As $\Delta[A]$ declines to zero, so does the concentration cell voltage. When the concentration cell is switched off, the AMS reseparates species A and restores the $\Delta[A]$ to its original equilibrium value, in which case it can be used again. Actually, because the AMS and concentration cell are chemically 'orthogonal,' they can be operated simultaneously, allowing the AMCC to operate continuously.

The primary advantage of the thermal battery over voltaic cells is not its energy density, but rather its rechargeability. If an AMCC can be recharged several hundred times via thermal energy alone, then its effective energy density could be considered on par with or greater than that of a standard voltaic cell.

IV. IMPLICATIONS OF SLDS

The current trajectory of world energy use is unsustainable and, if not corrected, will probably precipitate climatic, ecological, and societal catastrophes (Andrews & Jelley, 2017; Bressler, 2021). Even strict compliance with the Paris Climate Accord will, at best, avert only the most serious effects. Much of this peril is due to the effects of carbon fuel consumption (i.e., coal, oil, and natural gas).

The world's dependence on carbon fuels is understandable. They offer tremendously high energy densities (~50 MJ/kg), are relatively inexpensive (e.g., gasoline is often cheaper than bottled water in the US), and the technologies for their discovery, extraction, purification, and use are well-honed, having been sharpened for more than two centuries. In all, the "energy business"—e.g., the discovery, extraction, processing, transportation, use, remediation of fossil (carbon) fuels—constitutes upward of 10% of the global economy.

Alternative energy sources face daunting competition. Even if SLDs are proven viable in the laboratory, it is unclear whether they could be made economically competitive against standard energy sources. Scientific viability and economic competitiveness are two different issues. If successful, however, their ramifications might be profound, salutary, and disruptive in almost every sense. Let's consider the relative magnitude of energy reserves. SLDs utilize heat (thermal energy). The total thermal energy content of the world's ocean, atmosphere, and upper crust is roughly 10,000 times greater than the world's known carbon fuel reserves. Anything with a temperature above absolute zero possesses it. Thermal energy surrounds us, it's free, and it's non-polluting. SLDs do not make energy merely renewable, they make it recyclable. Energy can be used again and again in an endless cycle.

To understand the magnitude of this thermal energy reserve, consider a couple of domestic examples. Consider a cubic meter of air, a volume roughly half that of a typical office desk. The mass of that air is roughly 1.2 kg. The average speed of the air molecules is roughly 500 m/s, which is nearly 1.5 times the speed of sound, or roughly that of a medium-speed bullet. Now imagine being hit by such a bullet weighing about two-and-a-half pounds—what a mess! The kinetic energy of this cubic meter of air is roughly equivalent to the energy liberated in detonating 60 grams of the high explosive TNT. Water is even richer in thermal energy. The heat liberated in cooling a cubic meter of water from room temperature (T = 20 °C) down to its freezing point (T = 0 °C) and then freezing it is equivalent to the chemical energy released in detonating about 100 kg of TNT—enough to blow up a house.

The significance is this: There's virtually unlimited thermal energy in our environment, but it's generally overlooked because we don't see or feel it. In everyday scenarios, molecular motions are randomly oriented, working against each other—negating each other for purposes of doing work. (The second law sees to this.) Furthermore, we've learned to overlook the possibilities of thermal energy because of our belief in the second law's absolute status.

SLDs utilize ambient thermal energy so their fuel is free and effectively limitless. They emit no greenhouse gases and should be non-polluting, aside from the products used in their manufacture and retirement. Some proposed SLDs would use common and benign household chemicals. Overall, economically competitive SLDs would probably be positively disruptive. Their technology, of course, would have to be developed and adapted to the current uses for carbon fuels. History suggests that this conversion might take at least 3 to 4 decades.

In summary, a number of second law challenges share a common template. In theory, some offer high energy densities and other attractive features. It remains an open question, however, whether any can be translated into commercially viable technologies. Much may depend on the answer to this question.

NOTES

[1] An example of this occurred in 1998 when it was discovered that the cosmos is expanding faster than it ought. Because something was *changing* that could not be accounted for with known types of energy, a new type of energy was posited: *dark energy*. Indeed, this might be a new type of energy—although other explanations have been advanced—but in the interests of the first law, it was invented.

[2] Like many religious commandments, the second law is often stated as a prohibition rather than as a permission or directive.

[3] The renowned 20th-century physicist Wolfgang Pauli famously quipped, *God made the bulk; surfaces were invented by the devil*. Given the historical significance of Maxwell's demon with the respect to the second law and the current role of surfaces in its downfall, Pauli's statement is ironic and prescient.

[4] It is emphasized that not all SLDs share this template. For example, some supradegenerate and ideal gas systems rely on bulk processes to drive their SLD behaviors, rather than surface–boundary thermodynamic asymmetries (Item (1)).

[5] It is presumed that the systems start in thermal equilibrium with their environments (assumed infinite in extent and in thermal energy content).

[6] When an organism dies these concentrations differences relax, between parts of the cell, between inside and outside the cell, as the organism's molecules glide toward thermodynamic equilibrium with the environment.

[7] *No device is possible that operates in a cycle and whose sole net effect is to transfer heat from a cooler body to a hotter body.* In the colloquial: *Heat spontaneously conducts from hot to cold, not vice versa.* For example, one often sees ice melt in a hot drink, but one never sees cold tea spontaneously heat up while just sitting around.

[8] Think of a boring art exhibit attended by mutual strangers.

[9] There they are probably dearly hoping they won't run into a wall and be forced to eat another white chocolate Hershey kiss with a stale almond at the center. Unfortunately, their walks are random so they have no control over whether or when they hit another wall—rules are rules, after all. Fortunately, the boxes are scarce at the left end of the corridor.

[10] This might be a dumpster full of valuable Star Wars memorabilia (Lisbeth Accomando, private communication, 2022).

[11] Now the left-corridor unfortunates, who had to endure eating white chocolate Hershey kisses with stale almond centers, have won their reward and, at the very least, they can now afford some decent chocolate.

[12] A critical aspect of the AMCC is that its anode grows (precipitates AgCl), while its cathode corrodes (loses AgCl). For the system to behave as a true SLD, the anode and cathode must be regularly flipped in order for them to maintain their masses.

ACKNOWLEDGMENTS

The author gratefully acknowledges the insights, comments, and assistance of D. Miller, T. Zawlacki, T. Welsh, A. Watson, G. Hathaway, A. B. Accomando, P. C. Sheehan, and W. F. Sheehan. Technical support for this article was provided by C. Ibarra. The author thanks G. Moddel and C. Chase for inviting this article and the two reviewers for their helpful suggestions. This research was partially supported by the Laney and Pasha Thornton Foundation.

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RESEARCH ARTICLE

Type-B Energetic Processes and Their Associated Scientific Implications

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SUBMITTED March 7, 2022
ACCEPTED August 15, 2022
PUBLISHED October 22, 2022

https://doi.org/10.31275/20222517

HIGHLIGHTS

New research reveals a new energy process that uses limitless heat energy in the environment to do useful work like creating electricity.

ABSTRACT

Recently, our work has identified two thermodynamically distinct types (A and B) of energetic processes naturally occurring on Earth. Type-A energy processes such as the classical heat engines, ATP hydrolysis, and many of the known chemical, electrical, and mechanical processes apparently follow well the second law of thermodynamics; Type-B energy processes, for example, the newly discovered thermotropic function that isothermally utilizes environmental heat energy to do useful work in driving ATP synthesis, follow the first law of thermodynamics (conservation of mass and energy) but do not have to be constrained by the second law, owing to its special asymmetric functions. In mitochondria, special asymmetric functions associated with Type-B processes comprise: 1) Transmembrane-electrostatic proton localization; 2) The transmembrane asymmetry of inner mitochondrial membrane structure with the protonic outlets of redox-driven proton-pumping protein complexes protruded away from the membrane surface by about 1–3 nm into the bulk liquid p-phase while the protonic inlet of the F_0F_1-ATP synthase located at the transmembrane-electrostatically localized proton (TELP) layer; and 3) The lateral asymmetry of mitochondrial cristae with an ellipsoidal shape that enhances the density of TELP at the cristae tips where the F_0F_1-ATP synthase enzymes are located in support of the TELP-associated thermotrophic function. The identification of Type-B energy processes indicates that there is an entirely new world of physical and energy sciences yet to be fully explored. Innovative efforts exploring Type-B processes to enable isothermally utilizing endless environmental heat energy could help liberate all people from their dependence on fossil fuel energy, thus helping to reduce greenhouse gas CO_2 emissions and control climate change, with the goal of a sustainable future for humanity on Earth.

KEYWORDS

Thermodynamic–spatial asymmetry, isothermal environmental heat energy utilization, thermotrophic function, negative entropy, transmembrane electrostatically localized protons, asymmetric biomembrane structure

The transmembrane-electrostatic proton localization is a protonic capacitor be

Identification of Type-B Energetic Processes

Physical sciences, including chemistry and biochemistry, are intimately linked with energetics. In centuries past, probably due to monolithic thinking about the second law of thermodynamics, it was widely believed that environmental heat energy (which is the dissipated form of thermal (heat) energy, also known as latent heat or the temperature-dependent molecular thermal motion kinetic energy in the environment), could not be utilized to do useful work unless there is a temperature gradient or difference. That is also known as one of the classic rules for the second law of thermodynamics (Nikulov, 2011; Pisano et al., 2019; Sheehan, 2012). Recently, through bioenergetics elucidation studies with the transmembrane-electrostatically localized protons (TELP) theory (Lee, 2005, 2012, 2013, 2015, 2019a, 2020c; Saeed & Lee, 2018), it was surprisingly revealed that environmental heat energy can be isothermally utilized through TELP at a liquid-membrane interface to help drive ATP synthesis in many biological systems (Lee, 2017, 2018, 2019c, 2019e, 2019f, 2020b) including mitochondria (Lee, 2021b). This finding indicated that the protonic bioenergetic systems have a thermotrophic feature that can isothermally utilize environmental heat (dissipated-heat energy) through TELP with asymmetric membrane structures to generate significant amounts of Gibbs free energy to drive ATP synthesis (Lee, 2017, 2018, 2019c, 2019d, 2019e, 2019f, 2020b). This has now led to an important discovery: there are two thermodynamically distinct types (A and B) of energetic processes naturally occurring on Earth (Lee, 2021b).

Type-A energy processes such as classical heat engines, and many of the known chemical, electrical, and mechanical processes apparently follow well the second law; Type-B energy process as exemplified by the thermotrophic function that isothermally utilizes environmental heat energy associated with TELP does not necessarily have to be constrained by the second law, owing to its special asymmetric function (Lee, 2020a, 2021b). The discovery of Type-B energy process indicates that there is an entirely new world of physics, chemistry, and biochemistry yet to be fully explored.

Key Factors in the Protonic Thermotrophic Function as a Type-B Energetic Process

We now understand that the protonic thermotrophic function as a Type-B energy process is enabled through two key factors (Figures 1 and 2): 1) transmembrane-electrostatic proton localization, and 2) the asymmetric structures of biological membranes.

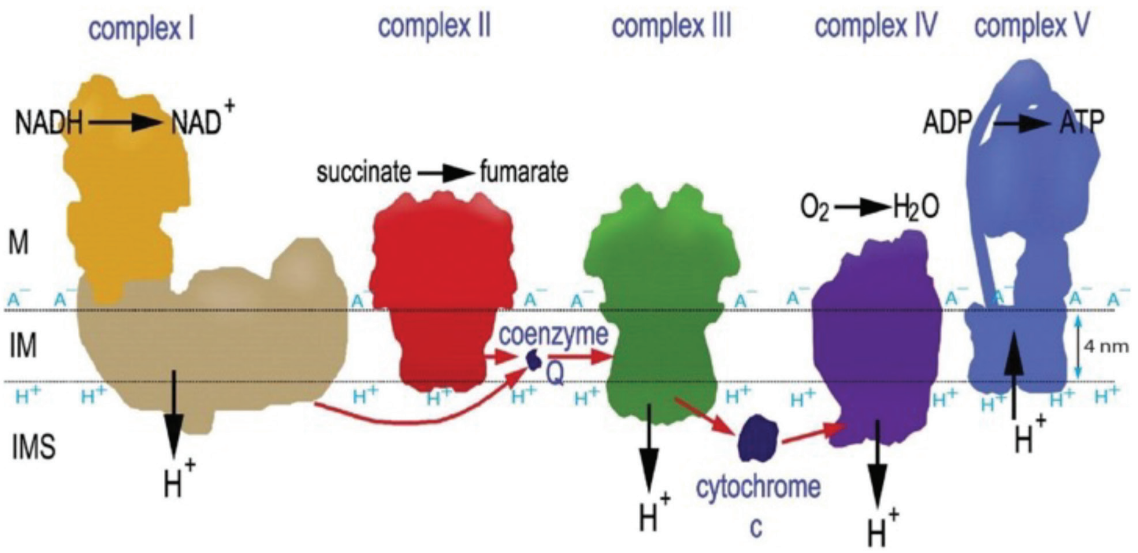

Figure 1. The transmembrane asymmetric structure is one of the key factors that enable isothermal environmental heat energy utilization as a Type-B process to do useful work in driving ATP synthesis. This figure presents the known structures of mitochondrial respiratory membrane protein complexes I, II, III, IV, and F_0F_1-ATP synthase (complex V) in relation to the location of the membrane surfaces indicated by the horizontal dotted lines. The thickness of the membrane lipid bilayer (in between the horizontal lines) is known to be approximately 4 nm, with which as a reference frame the protonic outlets of the proton pumping complexes I, III, and IV are seen to be all protruded by approximately 1–3 nm into the bulk liquid phase, while the protonic inlet of F_0F_1-ATP synthase (complex V) is located at the transmembrane-electrostatically localized proton layer along the membrane surface. Adapted from Lee (2020b), which was adapted and modified from a schematic representation of the oxidative-respiratory phosphorylation system given in Dudkina et al. (2010).

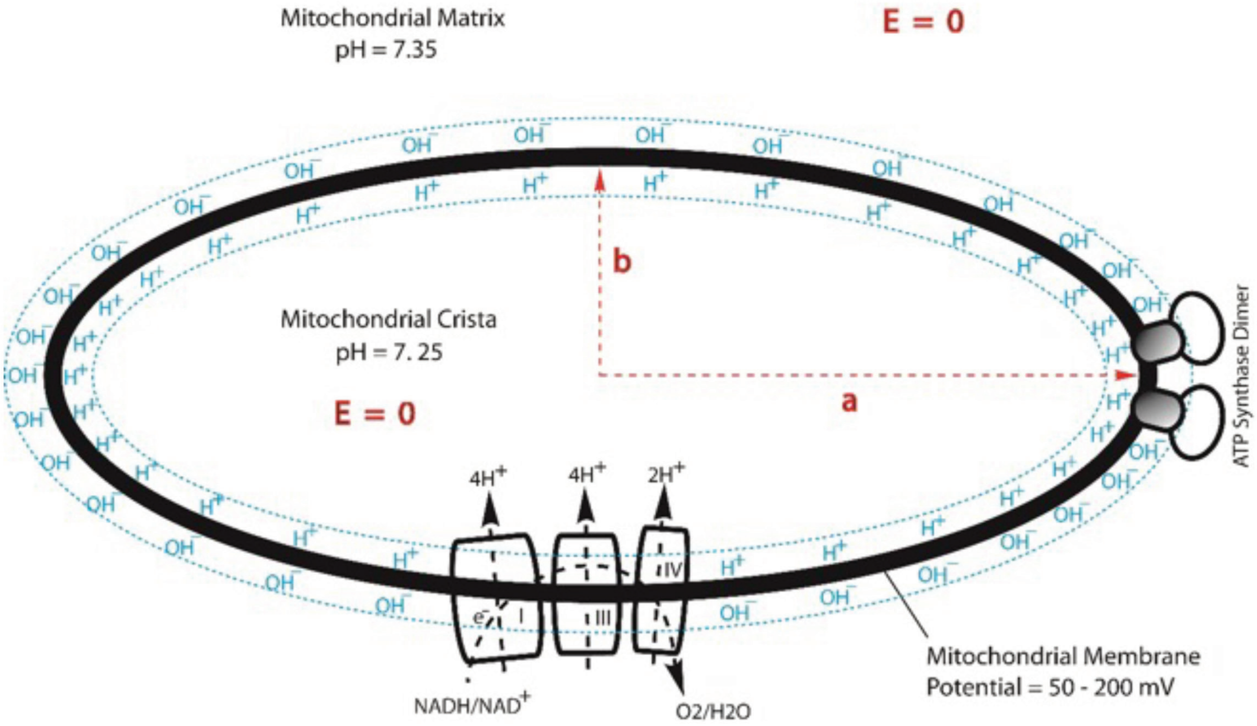

Figure 2. The protonic capacitor formation through transmembrane-electrostatic proton localization is another key factor that enables isothermal environmental heat energy utilization as a Type-B process to do useful work in driving ATP synthesis. This figure illustrates: the lateral asymmetric feature resulting from the geometric effect of mitochondrial membrane cristae, which enhances the density of transmembrane electrostatically localized protons at the cristae tips where the F_0F_1-ATP synthase enzymes reside in contrast to those at the relatively flat membrane region where the proton pumping complexes I, III, and IV stay as shown in a cross-section for an ellipsoidal-shaped mitochondrial crista. Adapted from Lee (2020c).

The transmembrane-electrostatic proton localization is a protonic capacitor behavior that stems from the property of liquid water as a protonic conductor and the mitochondrial inner membrane as an insulator (Figures 1 and 2). Consequently, the creating of an excess number of protons on one side of the mitochondrial inner membrane accompanied by a corresponding number of hydroxyl anions on the other side, for instance, through the redox-driven electron-transport–coupled proton pumps across the membrane, will result in the formation of a protonic capacitor across the biomembrane as shown in Figures 1 and 2. Accordingly, the excess positively charged protons in an aqueous medium on one side of the mitochondrial inner membrane will electrostatically become localized as TELP at the liquid-membrane interface, attracting an equal number of excess negatively charged hydroxyl anions to the other side (matrix) of the mitochondrial inner membrane to form a "protons-membrane-anions capacitor structure" (Lee, 2005, 2012, 2013, 2015, 2019a, 2019c, 2020b, 2020c, 2020d). The TELP activity at the liquid-membrane interface is now known to contribute to the amount of local protonic Gibbs free energy (ΔG_L) according to the following equation:

$${}_L = -2.3\ RT\ \log_{10}(1 + [H_L^+]/[H_{pB}^+]) \qquad (1)$$

Here, $[H_L^+]$ is the TELP concentration at the membrane-liquid interface at the positive (p)-side; $[H_{pB}^+]$ is the bulk liquid phase proton concentration at the same p-side in the mitochondria intermembrane space and cristae space; R is the gas constant; and T is the environmental temperature in Kelvin.

The ratio $[H_{pB}^+]$ / $[H_{pB}^+]$ of the localized proton concentration $[H_L^+]$ at the membrane-liquid interface to the bulk liquid-phase proton concentration $[H_{pB}^+]$ at the same side in the mitochondria intermembrane space and cristae space is related to the "negative entropy change" (ΔS_L), as shown in the following quantitative expression:

$$\Delta S_L = -2.3\ R\ \log_{10}(1 + [H_L^+]/[H_{pB}^+]) \qquad (2)$$

As you can see in this local protonic entropy (ΔS_L) Equation 2, if TELP concentration $[H_L^+]$ is above zero, the entropy change (ΔS_L) is mathematically shown here as a negative number. That is, the entropy change for the isothermal environmental heat utilization function as a Type-B energy process is indeed negative as long as the localized proton concentration $[H_L^+]$ is above zero in the mitochondria.

The transmembrane asymmetric structure (Figure 1) such as the protonic outlets of proton-pumping protein complexes I, III, and IV protruded away from the membrane surface by approximately 1–3 nm into the bulk liquid *p*-phase (intermembrane space, IMS) while the protonic inlet of the ATP synthase (complex V) located rightly at the localized proton layer along the membrane surface enables effective utilization of TELP with their thermal motion kinetic energy (k_BT) to do useful work in driving the rotatory molecular turbine of F_0F_1-ATP synthase for ATP synthesis. Consequently, the mitochondria can isothermally utilize the low-grade environmental heat energy associated with the 37 °C human body temperature to perform useful work driving the synthesis of ATP with TELP. Fundamentally, it is the combination of protonic capacitor and asymmetric membrane structure that makes this amazing thermotrophic (Type-B energy process) feature possible.

Furthermore, there is a lateral asymmetric feature from the geometric effect of mitochondrial cristae (a crista typically with an ellipsoidal shape is a fold in the inner membrane of a mitochondrion) that enhances the density of TELP at the cristae tips (Lee, 2020c), where the F_0F_1-ATP synthase enzymes are located (Figure 2) in supporting the thermotrophic function. As recently reported (Lee, 2020c), the ratio of the TELP concentration at the crista tip ($[H_L^+]^0{}_{tip}$) to that at the crista flat membrane region ($[H_L^+]^0{}_{flat}$) equals the axial ratio (a/b) of an ellipsoidal mitochondrial crista. Consequently, for an ellipsoidal crista with a length of 200 nm and a width of 20 nm, the TELP concentration at the crista tip ($[H_L^+]^0{}_{tip}$) can be as high as 10 times that of the flat region ($[H_L^+]^0{}_{flat}$). This lateral asymmetric effect translates to a TELP-associated liquid-membrane interface pH difference of approximately one pH unit between the crista tip (ridge) and the flat region within the same crista. It is now known that the proton-pumping "respiratory supercomplexes" (complexes I, III, and IV) are situated at the relatively flat membrane regions where the TELP concentration ($[H_L^+]^0{}_{flat}$) is relatively lower, whereas the ATP synthase dimer rows are located at the cristae ridges (tips) where the TELP concentration ($[H_L^+]^0{}_{tip}$) is significantly higher, as shown in Figure 2 (Blum et al., 2019; Davies et al., 2011, 2012, 2018; Guo et al., 2018; Kühlbrandt, 2015; Lee, 2020c). Consequently, even if the protonic outlets of complexes I, III, and IV are somehow in contact with the TELP layer at the crista flat membrane region so that their activities would be equilibrated with the redox potential chemical energy limit ΔG_{Chem} (–22.0 kJ mol^{-1}), the total protonic Gibbs free energy (ΔG_T) at the crista tip can still be as high as –27.9 kJ mol^{-1} since the TELP density at the crista tip can be as high as 10 times that of the crista flat region, equivalent to an additional effective protonic Gibbs free energy of –5.89 kJ mol^{-1} owing to the crista geometric effect on TELP at the liquid-membrane interface (Lee, 2020c).

Note that when the axial ratio (*a/b*) equals unity (one) for a round sphere (symmetric), the density of TELP would be the same at any spot along the liquid-membrane interface for the entire spherical membrane system. Therefore, we now further understand that the ellipsoidal (asymmetric) vs the spherical (symmetric) shape change represents another revenue of spatial asymmetry that enables a lateral asymmetric TELP distribution along the crista liquid-membrane interface to increase TELP density at the crista tip (relative to the crista flat region) to enhance the TELP-associated thermotrophic function.

As a folksy summarizing description for the protonic capacitor, its two charge layers across the biomembrane creates a voltage, like a self-contained protonic battery (Figures. 1 and 2). The protonic battery can then drive protonic flow through the nanometer-scale molecular turbine of F_0F_1-ATP synthase to synthesize ATP from ADP and Pi. The assembly line for the reactions of biomembrane system is illustrated in Figure 1, which depicts the various biochemical factories (Complexes I–V) that carry out these processes. Namely, Complex I, III, and IV consume redox chemical energy to pump protons across the membrane through their protruded protonic outlets (asymmetric feature) into the bulk liquid phase (to avoid contact with the TELP layer) while the protonic mouth of F_0F_1-ATP synthase (Complex V) is rightly positioned within the TELP layer to utilize the protonic energy. Furthermore, the geometric effect of mitochondrial membrane cristae (lateral asymmetric feature) enhances TELP density at the cristae tips where the F_0F_1-ATP synthase enzymes reside (Figure 2) for the utilization of the protonic energy to drive the synthesis of ATP that the cells can use.

Isothermal Absorption (Utilization) of Environmental Heat Energy Owing to Thermotrophy

When TELP-associated thermotrophic activities utilize mitochondrial environmental heat energy (k_BT) in driving the molecular turbine of F_0F_1-ATP synthase for the synthesis of ATP from ADP and Pi, as discussed in Lee (2020b),

> a fraction of the environmental heat (k_BT) energy may consequently be locked into the chemical form of energy in ATP molecules; and it would thus result in a small drop in the environmental temperature theoretically because of the TELP-associated isothermal environmental heat utilization.

However, in mitochondria and the cells,

> there are other processes (including the glycolysis, tricarboxylic acid cycle, and the redox-driven proton-pumping electron transport activities as well as the ATP utilization processes such as ATP hydrolysis) releasing heat energy, which could mask the thermotrophic function that features as the isothermal environmental heat energy utilization process.

Therefore, the energetic phenomenon in mitochondria (and the cells) may represent an interconnected mixture of both chemotrophic and thermotrophic processes. This subtle complexity has taken a long time to be understood.

We expect that when the release of heat energy from chemical energy and metabolism is limited such as under anaerobic conditions, isothermal environmental heat utilization of thermotrophic activities could still be detected directly by monitoring heat absorption through measuring the system temperature changes. Such an isothermal environmental heat absorption (utilization) has indeed been observed in an anaerobic liquid culture of *Methanosarcina sp*. cells in the experiments conducted by the author. Experimental results demonstrated that the temperature of *Methanosarcina* liquid cell culture was observed to substantially decrease by approximately 0.10 °C, and sometimes by as much as 0.45 °C, in comparison with the control (liquid medium without cells) (Lee, 2023 in press). This is significant since it experimentally demonstrates isothermal absorption (utilization) of environmental heat energy owing to thermotrophy.

Thermotrophy-Associated Protonic Bioenergetic Systems as Type-B Energetic Processes Operate Widely in Natural Environments

The thermotrophy-associated protonic bioenergetics systems widely operate in nearly all organisms known today. It is now also clear that this special thermotrophic process associated with TELP has probably already been occurring on Earth for billions of years. Therefore, we have now identified two thermodynamically distinct types (A and B) of energy processes naturally occurring on Earth, based on their properties and whether they follow the second law of thermodynamics or not. As mentioned before, Type-A energetic processes include glycolysis, tricarboxylic acid cycle, redox-driven electron transport, and many of the known chemical reactions and processes in our test tubes, computers, and cars that apparently follow the second law. Type-B energetic processes represented here by the thermotrophic function (Figures 1 and 2) do not have to be constrained by the second law, owing to their special asymmetric functions. That is, the second law still remains a valid law. However, it does not necessarily have to be universal, as indicated by a number of independent studies (Battail, 2009; Jennings et al., 2018; Koski et al., 2014; Lee, 1983, 2017, 2019b; Pal et al., 2014; Serreli et al., 2007; Sheehan, 2012, 2018; Sheehan et al., 2012, 2014; Vologodskii et al., 2001).

We now have at least three well-defined biosystems: mitochondria (Lee, 2021b), alkalophilic bacteria (Lee, 2020b), and methanogen *Methanosarcina* (Lee, 2023 in press) with well-corroborated scientific evidence showing the special Type-B process that perfectly follows the thermodynamic first law (conservation of mass and energy), but which are not constrained by the second law of thermodynamics. As shown in Equation 2, the entropy change (ΔS_L) for TELP-associated isothermal environmental heat utilization was calculated indeed to be a negative number. Therefore, the new understanding of the Type-B process may represent a complementary development to the second law of thermodynamics and its applicability in bettering the science of bioenergetics and energy renewal.

Type-B Energetic Processes: The Second Law of Thermodynamics Does Not Necessarily Have to Be Universal

We all understand that the second law remains an incredibly good law. However, it does not necessarily have to be absolute or universal, as indicated by well-documented independent studies (Battail, 2009; Čápek & Bok, 1999; Jennings et al., 2018; Koski et al., 2014; Lee, 1983, 2017, 2019b; Pal et al., 2014; Serreli et al., 2007; Sheehan, 2012, 2018; Sheehan et al., 2012, 2014; Vologodskii et al., 2001). The special Type-B process perfectly follows the first law of thermodynamics (conservation of mass and energy) but does not obey the second law. In other words, the TELP-associated thermotrophic function as a Type-B process clearly represents an example of a natural "second law violation," since the Type-B process by definition is not constrained by the second law.

Note that the second law of thermodynamics was developed from the Sadi Carnot cycle (Saslow, 2020) that was based on the ideal gas law ($nRT = PV$; where P is pressure, V is volume, and n is the number of moles) where the ideal molecular particles were assumed to have freedoms in

3-dimensional space (volume) without the consideration of any asymmetric structures. In the case of protonic bioenergetic systems, TELP (Lee, 2005, 2012, 2013, 2015, 2019a, 2019c, 2020b, 2020c, 2020d) are on a two-dimensional membrane surface with asymmetric properties, which is quite different from the assumed three-dimensional space (volume) system that the second law was based on. Therefore, one must be careful not to mindlessly apply something like the second law, which is derived from a three-dimensional space (volume) system, to a two-dimensional and/or one-dimensional system without looking into the specific facts.

Furthermore, the thermodynamic-spatial asymmetric features that may be human-made (Lee, 2021a; Mangum et al., 2021; Sheehan et al., 2014) and/or resulting from the billion years of natural evolution were not considered by the formulation of the second law per se; this is another reason that one should be careful not to apply the second law mindlessly with monolithic thinking or blindly to certain special cases involving asymmetric systems without looking into the specifics.

This type of basic scientific principle has been well communicated in the biochemistry field of enzyme kinetics. For example, the textbook Michaelis–Menten enzyme kinetics equation, like a "law," can be very useful to analyze the mechanisms for many of the enzymes. It is also well taught in many textbooks that one must be careful not to blindly apply the Michaelis–Menten equation to certain enzymes, such as the allosteric enzyme hemoglobin, which "diverge[s] from Michaelis–Menten behavior" (Garrett & Grisham, 2013; Nelson & Cox 2013). This is due to the fact that the Michaelis–Menten equation is based on its steady-state assumption, where the concentration of the enzyme–substrate complex (ES) is assumed to quickly reach a constant value (so that $d[ES]/dt = 0$, which makes the differential equation system solvable in obtaining the Michaelis–Menten equation). Whereas, its assumption of "$d[ES]/dt = 0$" and thus the Michaelis–Menten equation are not applicable to the allosteric enzyme hemoglobin. Something similar can now be said about the applicability of the thermodynamic second law: The second law is highly valuable when being properly applied to Type-A energy processes, but not necessarily for Type-B energy processes.

That is, the second law can be applied to Type-A processes such as classical heat engines, and many of the known chemical, electrical, and mechanical processes where the second law belongs. The second law should not be blindly applied to Type-B energy processes owing to their special asymmetric functions. It is important now for our scientific communities to avoid monolithic thinking and keep an open mind to consider Type-B processes and their related phenomena in certain physical, chemical, and/or biological processes, especially where asymmetric mechanisms are involved. The scientific communities may well benefit from the new fundamental understanding of Type-B processes uncovered in Earth's natural environment. To avoid blind faith in the second law, the scientific community must pay attention to what this law was really based on and to better understand its limitations, which are of great scientific and practical importance.

Better Messages Regarding Type-B Energetic Processes to Educate Scientific Communities and the Public for a Shared Sustainable Future on Earth

We now understand that many of the recent scientific explorations regarding questions on the second law of thermodynamics, such as the recent studies of Sheehan et al. (2012, 2014) and Nikulov (Gurtovoi et al., 2019; Nikulov, 2011, 2021, 2022) are legitimate and excellent and thus should be encouraged in order to move the field forward. In hindsight, however, some of the phrases used in the past such as "challenging the second law of thermodynamics" (Cápek et al., 2005; Eling & Bekenstein, 2009; Nikulov, 2011; Sheehan et al., 2012) appear to be somewhat inaccurate, or did not seem to carry exactly the right messages for the scientific community. This could in part explain why so far they still have not been well received by many in the scientific community, who may feel the second law serves their research very well, and for good reasons. In fact, to many in the scientific community who may be familiar only with Type-A processes, the term "challenging the second law of thermodynamics" could be misunderstood as "challenging" the basis of their careers, which might have been built largely on classic thermodynamic second law as taught in textbooks. Consequently, some may feel upset or annoyed, with an attitude of "total disbelief," and quite often tend to completely ignore or reject the topic.

Somewhat like the Michaelis-Menten equation that works well with many known enzymatic processes, the second law of thermodynamics is indeed an excellent law within its own assumed basis and domain (the ideal gas law-based Carnot cycle), which can well explain Type-A processes. On the other hand, if one were to blindly apply the second law to a Type-B process, then the user would be unable to see what we can now see (e.g., thermotrophic activities). This would be somewhat analogous to blindly applying the Michaelis–Menten equation to hemoglobin and failing to see hemoglobin's beautiful allosteric cooperativity of oxygen binding activities on the enzyme essential for our life. Therefore, this author encourages the use of more accurate terms like "challenging the applicability (or universality) of the thermodynamic second law," since the second law is applicable to Type-A processes but may not necessarily be applicable to Type-B processes because of their special asymmetric functions.

For a world in which the second law is now known to not be absolute, biological Type-B processes may be harnessed by innovatively mimicking thermotrophic functions to utilize limitless environmental thermal energy to do useful work such as generating isothermal electricity to power the modern electricity-based world economy. For example, a novel invention on isothermal electricity for energy renewal has now been made to generate isothermal electricity by innovatively translating the concept of the asymmetric protonic membrane capacitor-enabled Type-B process into an isothermal electrons-based power generation system, which is referred as "an asymmetric function–gated isothermal electricity generator system" that could be made into a chip device (Lee, 2019b). Its isothermal electricity power density could be so surprisingly good that a chip size of approximately 40 cm^2 may be sufficient to continuously power a smart mobile phone device forever (Lee, 2021b). That is, based on this invention (Lee, 2019b), novel Type-B energy technologies such as asymmetric function–gated isothermal electricity generator systems have the potential capabilities to permanently power many electric devices, electric motors, machines, and vehicles including (but not limited to) mobile phones, laptops, cars, buses, trains, ships, and airplanes utilizing limitless environmental heat energy alone without requiring any fossil fuel energy (Lee, 2021b). Therefore, innovative scientific research and development efforts in mimicking and/or creating Type-B processes (Lee, 2021b) to isothermally utilize endless environmental heat energy (Gurtovoi et al., 2019; Lee, 2019b, 2021a; Mangum et al., 2021; Sheehan et al., 2014) should be highly encouraged to help ultimately liberate all people from their dependence on fossil fuel energy, thus helping to reduce greenhouse gas CO_2 emissions and control climate change toward a common shared sustainable future for humanity on Earth.

ACKNOWLEDGMENTS

The author (Lee) thanks the editors and anonymous peer reviewers for their highly valuable and constructive review comments that made this article better. This work was supported in part by the Lee laboratory start-up research funds provided by the Department of Chemistry and Biochemistry, the College of Sciences, the Office of Research at Old Dominion University, and by the Old Dominion University Research Foundation, and also in part by a Multidisciplinary Biomedical Research Seed Funding Grant from the Graduate School, the College of Sciences, and the Center for Bioelectrics at Old Dominion University, Norfolk, Virginia, USA. The energy renewal isothermal electricity invention (WO 2019/136037 A1) was made through a private scientific exploration effort outside Old Dominion University.

Competing interests. The author declares no competing interests.

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RESEARCH ARTICLE

Zero-Point Energy: Capturing Evanescence

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SUBMITTED April 6, 2021
ACCEPTED June 29, 2022
PUBLISHED October 22, 2022

https://doi.org/10.31275/20222567

HIGHLIGHTS

Combining quantum vacuum and nanoelectronic device concepts results in a novel energy-producing device that seemingly draws energy from the quantum vacuum.

ABSTRACT

In results from thousands of trials and dozens of variations, tests for measurement artifacts, and replications, metal/insulator/metal/Casimir cavity devices produce electric power, apparently by tapping ambient zero-point energy (ZPE). A simple calculation shows that the power potentially available from the ZPE quantum vacuum is an immense 5 gigawatts per square meter. The devices tap a tiny fraction of that, but still deliver a practical power density of 70 watts per square meter. The devices are designed to circumvent the apparent impediments to ZPE harvesting, i.e., that ZPE is the universal ground state, and that ZPE fluctuations are extremely short-lived and virtual. If the source ultimately proves to be ZPE, what is the operating principle behind the energy harvesting, and how can the results be reconciled with known physical law? A notional operating principle can be understood as a direct analog to the optical phenomenon of frustrated total internal reflection. Tapping ZPE does not violate the second law of thermodynamics based on the conventional quantum interpretation of ZPE, but ambiguities regarding the source of ZPE leave the issue unresolved.

INTRODUCTION

The concept of expending resources to obtain energy has remained with us for most of human history, with the mining of carbon-based fuels, reacting of nuclear fuels, and collecting of sunlight, etc., to provide energy. From that perspective, the harvesting of zero-point energy (ZPE), a still mysterious cache of ubiquitous energy, feels like a violation of the principles of the world as we have come to know it. Can we tap this energy, or would doing so violate fundamental principles?

It appears that our lab has, in fact, discovered and demonstrated a way to tap ZPE (Moddel et al. 2021a; Moddel, 2021c). In this article, I review how we have done this and describe the underlying issues. First comes ZPE basics, including for the first time how much power can be obtained from the quantum vacuum ZPE. This is followed by the technology we have developed to harvest it, and the results. Then, I examine the impediments to harvesting ZPE fluctuations, including a way to understand the extraction of energy from what are termed virtual particles. This article addresses whether harvesting ZPE would violate the second law of thermodynamics, and where the energy might ultimately be coming from. The appendices comprise the equations and calculations on the available power, and a description of the sanity checks that were carried out to investigate whether the results could be due to unaccounted for artifacts. We are still in the midst of discovery and this article represents our current understanding, which is certain to evolve over time.

ZERO-POINT ENERGY BACKGROUND INFORMATION

ZPE is the ground state energy of quantum mechanical systems in both empty space and matter. In empty space it results in electromagnetic field fluctuations (Milonni, 2013). In molecules and solids it excites vibrations (quantized as phonons) (Yang & Kawazoe, 2012). With the further addition of conducting carriers (such as electrons) it results in plasmonic fluctuations (collective charge oscillations) (Rivera et al., 2019).

In 1900, Max Planck developed his revolutionary theory for blackbody radiation that fills space. This thermal blackbody radiation for room temperature (300 K) is shown in Figure 1 as the curve that cups downward. It peaks at a photon energy of roughly 0.1 eV, corresponding to an infrared wavelength of 12 µm, and falls off before reaching the visible spectrum.

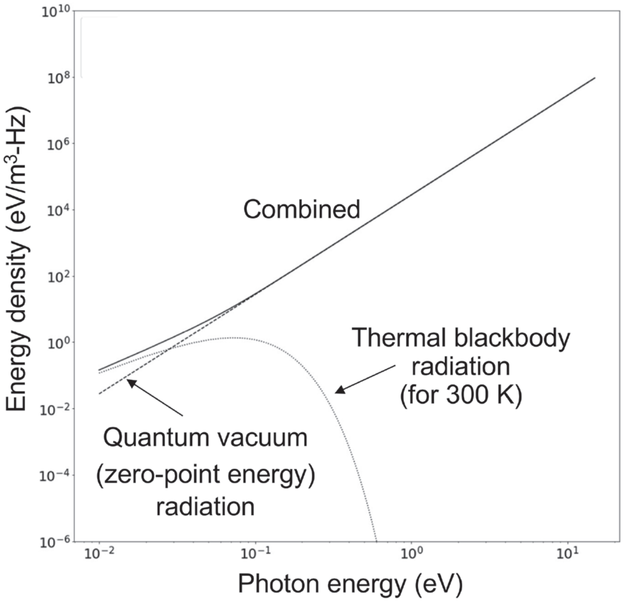

Figure 1. Energy density of background electromagnetic fields at room temperature (T = 300 K), as a function of photon energy (plot by Matt McConnell).

Eleven years after presenting his first theory Planck presented his second theory, which contained an additional, temperature-independent term. The full expression for the energy density of both the thermal blackbody, at temperature *T*, and ZPE components is

$$\rho(hf) = \frac{8\pi f^2}{c^3}\left(\frac{hf}{exp(hv/kT) - 1} + \frac{hf}{2}\right) \qquad (1)$$

where h is Planck's constant, f is the frequency of the radiation, and c is the speed of light (Milonni, 2013). Planck called the latter component, shown as the second term on the righthand side of the equation, *Restenergie* (rest energy) (Kragh 2012). Two years later, Albert Einstein and Otto Stern termed it *Nullpunktsenergie* (ZPE), because it exists even at a temperature of zero. In 1916, Nernst characterized ZPE as filling not only space (which he called the ether) but also material objects. At the time, Planck's second theory and the notion of ZPE was rejected by the physics community and only became increasingly accepted starting in 1926, when the uncertainty principle in the then-evolving quantum mechanics required it. The energy density for ZPE is shown as the straight line in Figure 1. At photon energies above those of mid-infrared light, the ZPE part of the energy spectrum dominates.

Usually, the energy density of ZPE is given, but that is not directly relevant to energy harvesting. For harvesting, it is the flow of energy, i.e., the power and the current, that matter. I derive the mathematical expression for those quantities in Appendix I, and find the cumulative magnitude up to a given (cutoff) photon energy. The cumulative current density grows with the third power of the cutoff photon energy (*hf*) and the power density with the fourth power of cutoff photon energy. The radiation passing through a given area can be expressed in terms of photon current, which is defined as the electrical current that would be produced if each incident photon generated the current from one electron. The ZPE cumulative photon current is shown in Figure 2.

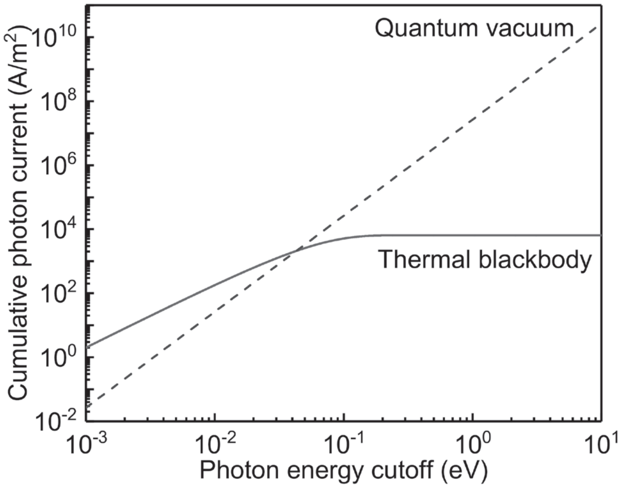

Figure 2. Cumulative photon current up to a cutoff photon energy from background electromagnetic radiation at room temperature, showing the thermal blackbody and quantum vacuum (zero-point energy) components. Photon current is defined as the electrical current that would be produced for each incident photon generating the current from one electron. The derivation of the expression for these currents is given in Appendix I.

The cumulative photon currents from the ZPE spectrum are huge. For example, the current produced for a cutoff photon energy of 4 eV, corresponding to a wavelength of 0.3 μm, is 1.7 GA m^{-2}, i.e., more than one billion amps per square meter. For comparison, a solar cell produces roughly 350 A m^{-2}.

The power available from the quantum vacuum for the same cutoff photon energy of 4 eV, as calculated in Appendix I, is 5.0 GW m^{-2}. For comparison, an entire full-size coal-fired power plant generates about 5 GW, the same amount of ZPE that passes through just one square meter. As described below, the power density that we have obtained so far is much lower than what is available, but even so it is sufficient to provide practical power levels.

DEVICE DESCRIPTION AND RESULTS

Device Structure

A depiction of the cross section of one of the devices being fabricated in our laboratory is shown in Figure 3(a). The device consists of an optical cavity deposited on top of a metal–insulator–metal (MIM) diode. The optical cavity, also called a Casimir cavity as discussed later in this article, consists of two reflective layers surrounding a transparent dielectric medium, either a polymer, polymethyl methacrylate (PMMA), or an oxide, SiO_2. The cavity thickness ranges from 33 nm to 1100 nm. The MIM diode consists of a semi-transparent palladium layer, 8.3 nm thick, and a thicker nickel layer surrounding a very thin insulator, ~2 nm in thickness. The insulator is thin enough for charge carriers to tunnel through it.

The devices are formed using microfabrication techniques described in Moddel et. al. (2021a). Although devices have been produced with a wide range of areas, those with submicron areas have produced the highest power density thus far. A scanning electron microscope image of one of the devices is shown in Figure 3(b). Its active region, formed at the overlap of palladium and nickel regions with a thin insulator in between, has an area of 0.02 μm^2. An optical Casimir cavity is formed over the MIM structure.

Results

The presence of an adjoining optical cavity results in a radical change in the current-voltage $I(V)$ characteristics of the MIM diode. Its resistance is greatly reduced (Moddel, 2021b), but more significantly, it produces power. The $I(V)$ curve for a device with a 33 nm thick transparent dielectric is shown in Figure 4(a). If an $I(V)$ curve does not pass through the origin it either uses or produces power (I x V), with the second and fourth quadrants of the $I(V)$ graph corresponding to power production.

The fact that the device produces power in the absence of any apparent input is remarkable. The area and $I(V)$ characteristics for the device shown correspond to a power production of 70 W/m^2. This is roughly one-third of the power per unit area produced by solar cells. Because this device is not optimized and can, in principle, be stacked, if the concept scales as it appears to, very substantial and practical power levels can be expected in the future.

As will be discussed later in this article, a signature of ZPE is an increasing deficit in energy density as the thickness of an optical cavity is reduced. The data of Figure 4(b) show just such a trend, with increasing power produced by devices for thinner cavities that are filled with PMMA or with SiO_2.

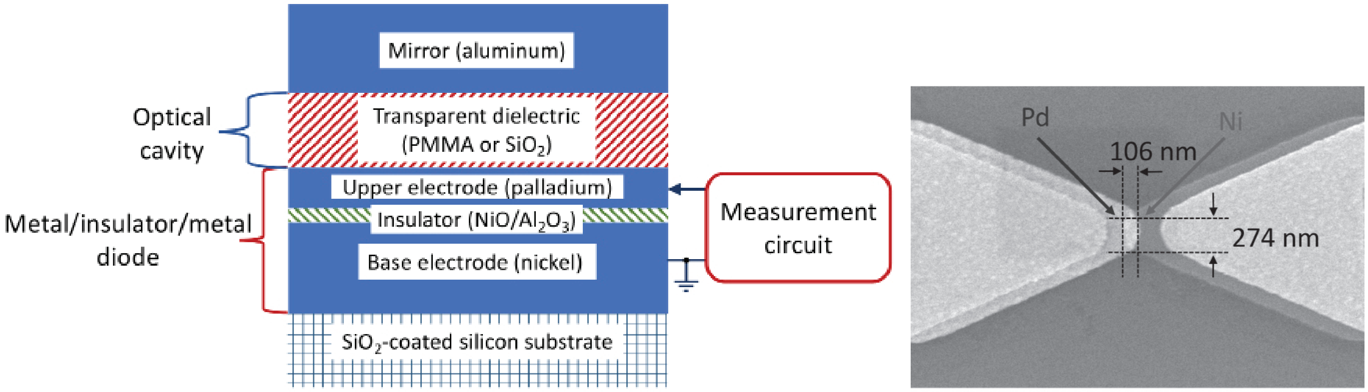

Figure 3. (a) Device cross-section, showing a metal–insulator–metal (MIM) structure adjoining an optical cavity. Positive current is defined to be in the direction of the arrow. **(b)** A scanning electron microscope (SEM) image of the top view of a completed MIM device. Both images are from Moddel (2021a).

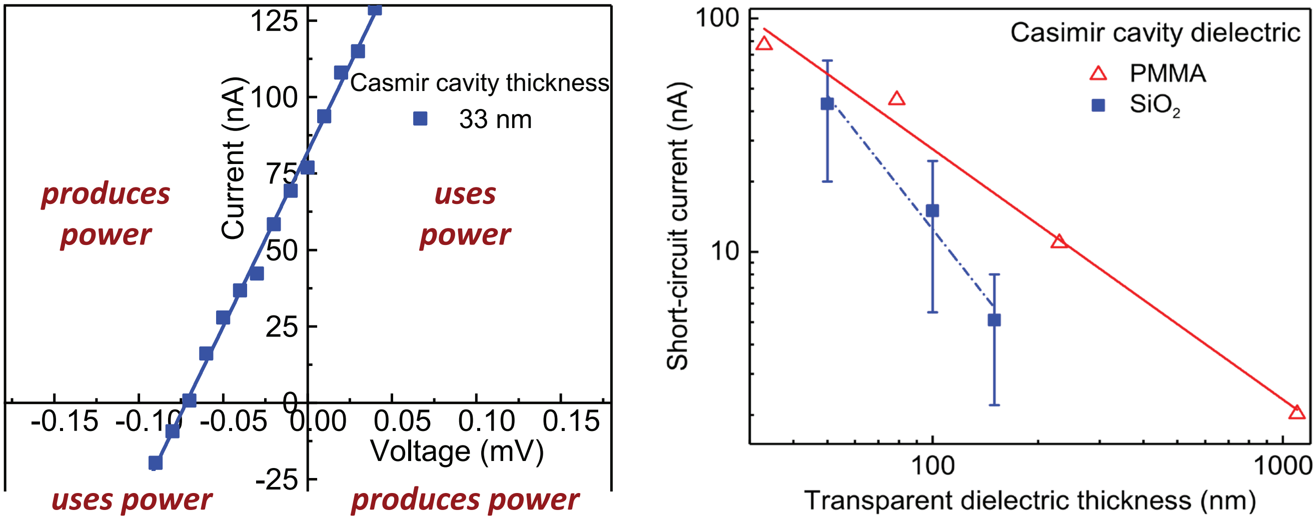

Figure 4. (a) Current as function of voltage for a device having a 33 nm cavity filled with PMMA. The curve passes through the second quadrant of the graph, corresponding to power production. The power density is 70 W/m^2. **(b)** Short-circuit current as a function of cavity thickness for PMMA and SiO_2–filled cavities (from Modde, 2021a). The output decreases with increasing thickness of the cavity, a signature of ZPE.

Testing for Artifacts

The trends shown here have been replicated in many thousands of devices produced in dozens of batches, although with significant device-to-device variation due to poorly controlled fabrication parameters in our current fabrication process. To analyze whether the devices are genuinely producing power, we carried out an in-depth investigation of nine possible artifacts (Moddel 2021a). The main points are summarized in Appendix II. No possible artifact that we are aware of can explain the observed results.

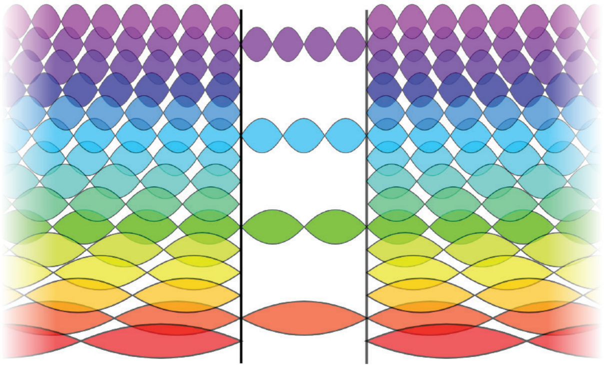

Figure 5. Depiction of optical modes in a Casimir cavity, where only limited wavelengths are allowed and long wavelength zero-point electromagnetic modes are suppressed (image from Kingsbury [2009]).

IMPEDIMENTS TO HARVESTING ZERO-POINT ENERGY

Universal Ground State

ZPE is the universal ground state, and it stands to reason that without a gradient (slope) or step in the ZPE density no flow can be induced. A change in this ground state can, however, be induced because it is geometry-dependent. In 1948, Hendrik Casimir proposed that the ZPE density in between two closely spaced mirrors would be lower than outside (Casimir, 1948). In particular, only zero-point electromagnetic modes having wavelengths of twice the optical cavity spacing divided by an integer are supported in this Casimir cavity, and all wavelengths greater than twice the spacing are suppressed. The reduction in mode density is depicted in Figure 5. As will be discussed, our devices make use of an adjoining optical cavity to provide a step in the ZPE density.

Short-Lived Fluctuations

The Heisenberg uncertainty principle limits the accuracy with which the values of certain complementary pairs of physical quantities are meaningful. One such pair is the energy and time, so that the lower the uncertainty is in the energy (ΔE) of a particle the greater the uncertainty must be in the time (Δt) that it is observable. In a vacuum, this means that large energy ZPE fluctuations can exist for only short times. For example, fluctuations having a photon energy of 2 eV (corresponding to red light), can exist for a time of only 0.16 fs (one femtosecond is 0.000000000000001 seconds). A theory has been proposed that an energy ΔE may be borrowed from the vacuum for a time Δt as long as it is paid back (Ford, 1991; Davies & Ottewill, 2002; Huang & Ford, 2015). The question I pondered is what would happen if the energy of the fluctuation were captured extremely quickly and in such a way that it could not be returned. As discussed in the Device Concept section, our devices make use of femtosecond capture of transitory energized particles.

Virtual Particles

When sufficiently energetic electromagnetic radiation strikes a metal surface, electrons are emitted, as depicted in Figure 6. This photoelectric effect was observed by Heinrich Hertz in 1887 and explained in terms of photon energy in 1905 by Einstein.

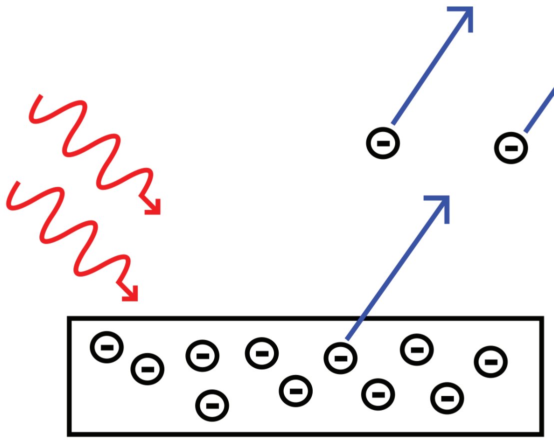

Figure 6. The photoelectric effect, in which incident electromagnetic radiation onto a metal surface produces the emission of electrons. (Image from Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Photoelectric_effect.svg)

Given the ubiquitous zero-point background electromagnetic fields shown in Figure 1, the question arises as to why we do not observe emission of electrons from all metal surfaces as a result of these fields. We can address this issue in terms of the short-lived nature of the fluctuations described in the previous section. For the example of 2 eV radiation (red light) presented above, the Δt is 0.16 fs. A simple calculation shows that in that time an electron would travel only 1 Å (0.1 nm), roughly an interatomic distance, before the borrowed fluctuation energy would be returned.

Another perspective on short-lived fluctuations is via the concept of virtual particles. Although the distinction between real and virtual particles is debated (Jaeger, 2019), ZPE quantum vacuum electromagnetic waves are generally considered to be virtual. Virtual waves and particles are transient quantum fluctuations whose existence is limited by the uncertainty principle, and which mediate interactions between other particles. Because they can be observed only through their effect on other particles, one cannot capture a “naked” virtual particle. They can, however, be converted to real particles. In the dynamical Casimir effect, effectively moving the mirrors of a Casimir cavity at high velocity has been shown to convert virtual fluctuations into real photons (Wilson et al., 2011). Can ultra-fast capture also convert virtual particles to real ones? By way of a comparison with evanescent optical modes, I argue that the answer may be yes.

Evanescent waves are oscillating electromagnetic waves that do not propagate; they just stay in one place. Such evanescent waves are equivalent to virtual photons (Stahlhofen, 2006). An evanescent wave is formed at the interface where total internal reflection occurs. Total internal reflection is an optical phenomenon that occurs in a prism where light is incident at an angle greater than a critical angle, as depicted in Figure 7(a). The evanescent wave extends beyond the prism and falls off exponentially within a fraction of wavelength. If a second prism is placed more than a wavelength away from the first, as shown in Figure 7(b), the evanescent wave is not affected. If, however, the second prism is placed within a small fraction of

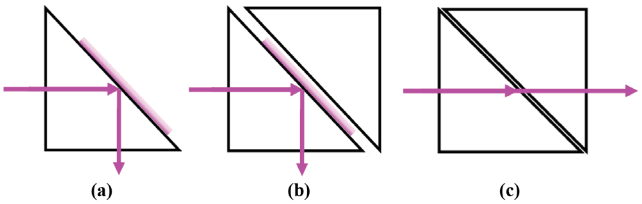

Figure 7. Converting evanescent waves into propagating waves. **(a)** Total internal reflection inside a prism, with an evanescent wave extending beyond the prism. **(b)** Second prism placed several wavelengths away from first prism does not affect the evanescent wave. **(c)** Second prism placed within a small fraction of a wavelength away from first prism frustrates the total internal reflection, resulting in a propagating wave. *A side note*: the evanescent coupling distance is limited by the same $\Delta E \Delta t$ uncertainty relation that controls zero-point fluctuations (Moddel, unpublished).

a wavelength from the first prism, evanescent coupling occurs; the previously stationary wave becomes a propagating wave, as depicted in Figure 7(c). In this way, the total internal reflection is frustrated (Hecht, 2017). The evanescent wave is turned into a propagating wave by the proximity of a second prism, a visible example of quantum tunneling through the narrow gap.

The same process is followed in our devices, in which an evanescent wave at a barrier becomes a propagating wave when the barrier region is sufficiently thin. This is depicted in Figure 8, where the incident wave is composed of electrons in a metal layer (such as the upper electrode in our device). The barrier is an insulator, and when that insulator layer is sufficiently thin some of the electron wave tunnels through and is transmitted to the second metal layer (the base electrode in our device). The energetic electrons are rapidly captured in the second metal layer. As described in the next section, this electron transport is the second step in a virtual particle chain.

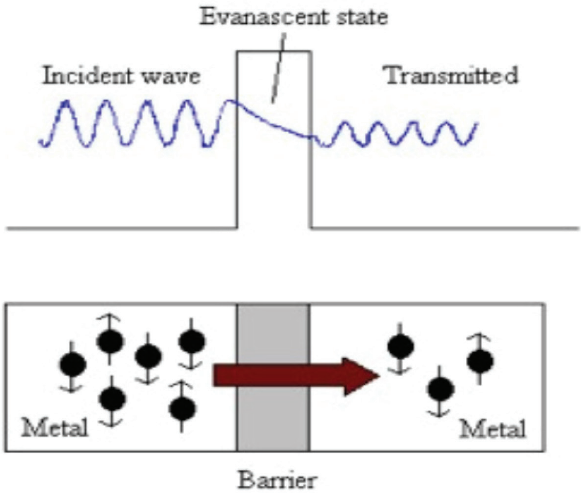

Figure 8. Evanescent coupling in a metal–insulator–metal device. The insulator forms a barrier through which the electron wave quantum mechanically tunnels, which is equivalent to evanescent coupling. Quantum tunneling is constrained by same $\Delta E \Delta t$ uncertainty relation that constrains zero-point fluctuations (Fertig, 1990). (Figure reproduced from Bhansali et al., 2010).

DEVICE CONCEPT

The device concept to harvest ZPE was developed five years ago, submitted as a provisional patent application three years ago, and the patent was issued recently (Moddel, 2021c). Subsequent experimental results have shown that an effective structure and the output characteristics of the device, depicted in Figures 3 and 4, closely follow what was predicted. As described below, it appears that the device works as a result of an asymmetry induced by the presence of an adjoining Casimir cavity. At this point, that model for the device operation is still speculative, and it is possible that the device structure has fortuitously enabled energy harvesting by a different mechanism. Here, I describe the apparent operating concept.

The ZPE harvesting device is based on MIM diodes, devices which our lab has been designing and fabricating for more than two decades to provide ultrahigh speed rectification (Grover & Moddel, 2012). These devices work by incorporating an ultra-thin barrier that allows charge carriers, electrons or holes, to tunnel through, as depicted in Figure 8. (Although the term “diode” usually refers to devices that allow current to flow preferentially in one direction, the MIM diodes do not necessarily exhibit asymmetry in current flow.) Tunneling through, or excitation over, the 1 to 3 nm thick insulator occurs in roughly 1 fs. The ZPE harvesting devices incorporate MIM diodes that have a base layer that is sufficiently thick (>35 nm) to be opaque, and a thinner (~10 nm) semitransparent upper electrode.

The photoelectric effect, depicted in Figure 6, produces emission of electrons at the free surface. If the metal layer is sufficiently thin, then the excited electrons also produce internal photoemission (also called photoinjection) at the internal surface. An MIM diode having a semitransparent upper electrode is depicted in Figure 9(a). At the upper surface, incoming zero-point radiation excites hot charge carriers that contribute to downward flow of charges. In addition, internal ZPE fluctuations in the upper electrode excite charges that contribute to that downward flow. The combined photoinjection and internally excited charges result in the downward flow depicted by the arrow on the left. The actual current that is produced is subject to the same constraints that block any ZPE-excited current in the photoelectric configuration shown in Figure 6. I term this loosely as a virtual current.

Similarly, internal ZPE fluctuations in the base electrode excite charges that result in an upward flow. There is no photoinjection current contributing to the upward charge flow because the base electrode is too thick for photoexcited charge generated at the lower surface to traverse the electrode to the insulator before being scattered. Because the base electrode is thicker than the upper electrode it produces more internally generated charge, so that the total upward charge flow is equal to the downward flow.

Now consider the same MIM diode, but with an adjoining Casimir cavity over the upper electrode, as shown in Figure 9(b). As discussed with regard to Figure 5, the zero-point electromagnetic mode density in a Casimir cavity is

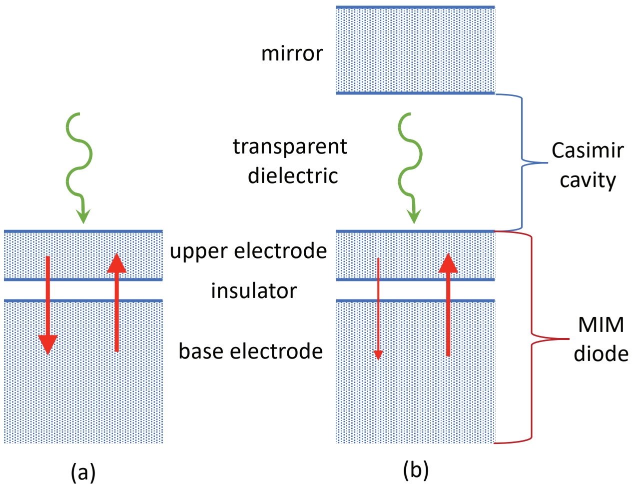

Figure 9. Device cross sections showing operating concept. **(a)** MIM diode with a thin upper electrode, which permits the photoinjection of charge from free space zero-point electromagnetic fluctuations. The downward flow of photoinjected charge plus internally excited charge is balanced by the upward flow of internally excited charge. **(b)** MIM diode with an adjoining Casimir cavity above the upper electrode, which results in suppression of photoinjection and reduces the downward flow of charge.

reduced as compared to the mode density in free space. Therefore, the photoinjection current is partially suppressed and the downward charge flow is reduced. Since the upward flow is not changed by the addition of the Casimir cavity, there is now a net flow of charge in the upward direction. This is a simplistic conceptual explanation for the current that we observe. The actual mechanisms are more complex and involve emission of electromagnetic modes into the cavity as well as absorption from the cavity, and are constrained by the transient nature of the zero-point excitations as required by the uncertainty principle, and can include contributions to the current from both electrons and holes.

I speculate on the chain of events that facilitates the capture of ZPE. Virtual photons strike the upper electrode and produce a virtual current of charge carriers that traverse the thin metal layer and the insulator, and are captured in the base electrode. Just as virtual photons that form an evanescent wave are converted to real, propagating photons in the presence of evanescent coupling, so too the virtual photons and subsequent virtual charge flow are converted into a real charge flow as a result of tunneling through the insulator and capture in the base electrode of our devices. As an alternative to invoking the notion of virtual particles, the $\Delta E \Delta t$ uncertainty relation limits the time available for the process to occur. If the transit and capture are completed within roughly 1 fs, then the energy may be captured; if not, then the energy is returned. Even if the process is not completed within the 0.16 fs described in the section on Short-Lived Fluctuations, some fraction of the available current can be collected, including from lower energy and hence longer-lived excitations. The presence of the adjoining Casimir cavity upsets the balance in virtual charge flow that would exist with it, so that the net flow of charge is upward.

This operating model is notional at best, and is far from rigorous. In contrast, a rigorous quantum model (Ford, 2022) has been proposed to explain the increase in conductivity that we observe due to an adjoining Casimir cavity (Moddel, 2021b), but it does not explain the observed power production.

LAWS OF THERMODYNAMICS

The second law of thermodynamics describes limits on the amount of heat that can be converted into work, and the inability of heat at the same temperature as its surroundings to be converted to work. There are multiple versions of the second law (Cápek & Sheehan, 2005), most of which involve the concept of temperature. Because ZPE exists even in the absence of temperature, to analyze the possibility of harvesting ZPE requires a version of the second law that does not involve temperature. Planck's version of the second law states, "Every . . . process occurring in nature proceeds in such a way that the sum of the entropies of all bodies which participate . . . is increased." Since work (including electrical power) has zero entropy, converting an entropy-containing source of energy, such as heat, would violate the second law unless the excess entropy is carried away via heat loss. Entropy is a measure of the number of options for the configuration of energy in a system. ZPE in free space is a unique ground state, the only option, and therefore has zero entropy (Boyer, 2002). For that reason, we are free to convert ZPE in free space to work without violating the second law.

The situation is different in a Casimir cavity, where the entropy is not zero and is associated with the cavity spacing (Revzen et al., 1997). Therefore, if the cavity spacing is varied as the energy is extracted, e.g., making use of the Casimir force to produce work, there will be a change in the entropy of the system. To avoid the need to decrease the entropy of the system and violate Planck's version of the second law, heat would then have to be expelled to carry the entropy away. This would limit how much, if any, of the ZPE could be converted to work. In the ZPE harvesting system described here, however, there is no change in the cavity spacing, and therefore no change in the internal entropy. Therefore, we are free to convert the ZPE to work without necessarily violating the second law.

If ZPE is being extracted from quantum vacuum fluctuations, a crucial question is what is the nature of the underlying source for that energy:

- ZPE is built into quantum mechanics, which leads to the disconcerting notion that if one were to extract ZPE from a closed system, the amount of ZPE in that system would remain unchanged. Extracting ZPE would then violate conservation of energy, the first law of thermodynamics, even if it did not violate the second law.
- An alternative view of ZPE is described by stochastic electrodynamics (Boyer, 1975), an intriguing but incomplete classical alternative to quantum mechanics in which space is filled with real electromagnetic ZPE that is dynamically exchanged between matter and space. A stochastic electrodynamics model would allow for extraction of ZPE without violating the first or second laws of thermodynamics.
- Finally, I speculate about a "thermal model," in which the source for ZPE is ultimately thermal. ZPE and thermal energy are intimately connected (Boyer, 2012), but the notion that there is an exchange of energy between these two entities is certainly not accepted. Despite that, if it were to turn out that draining the ZPE from a system ultimately tapped the thermal energy in the system, harvesting ZPE would then cool the system; that would violate multiple versions of the second law.

If our devices are in fact powered by ZPE, a study of the extraction process could help explain the ultimate source of that energy.

CONCLUSIONS

Are we somehow fooling ourselves? We have carried out many tests for artifacts and they have all come out negative (briefly described in Appendix II). Recently multiple labs that are known for measurement accuracy have tested our devices in highly controlled environments and reproduced what we measure (not yet published). We have observed consistent trends in dozens of different device runs and thousands of measurements.

What we observe is real, but what is it due to? I have a continuing debate with myself, and anyone else who pipes in, as to whether the energy production that we observe is from ZPE, or if there is there some other source. The power output requires an adjoining optical cavity, and varies inversely with the cavity thickness—consistent with a ZPE source. The output varies with insulator and upper electrode thickness in a way that is consistent with photoinjection. Recent observation has shown that the effect does not diminish with decreasing temperature (not yet published)—also consistent with a ZPE source.

The quantum electrodynamics theory for the quantum vacuum and ZPE is rigorous, but still ambiguous as to the nature of ZPE. New characteristics of the Casimir effect are still be discovered. Given the evolving nature of our understanding of ZPE, must theory lead and experiment follow? Looking at the history of scientific advancement, I think not. "We don't want to lose sight of the fundamental fact that the most important experimental results are precisely those that do *not* have a theoretical interpretation" (Anderson, 1990).

Why are there no other clear observations of ZPE harvesting despite various approaches that have been proposed (Moddel & Dmitriyeva, 2019)? Is it possible that my speculations are correct that the key is femtosecond capture of the energy, and our devices are (to the best of our knowledge) unique in their ability to extract and capture the energy so quickly?

This is a fascinating adventure. Even more significantly, if these devices are, in fact, harvesting ZPE, then the technology could be truly world-changing for a world that desperately needs a clean and relatively cheap power source. The devices we are currently fabricating are tiny, but device technology has repeatedly shown the capability of scaling up. If even a small fraction of the 5 GW/m^2 power that I calculated were available from the quantum vacuum, it would provide all the power that we need for the foreseeable future.

ACKNOWLEDGEMENTS

I gratefully acknowledge Ayendra Weerakkody, Dave Doroski, and Dylan Bartusiak, the team that designed, fabricated, and tested the devices described in Moddel (2021a), and more recent members of the team, Bradley Pelz and Kyuyoung Bae. I appreciate the comments on the manuscript provided by Matt McConnell and Swapnil Mhatre. Without the encouragement and support of Matt McConnell this endeavor would not have been possible. Much of the work was supported by The Denver Foundation, which I greatly appreciate, and more recently by Radanta Corporation.

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APPENDIX I: CALCULATION OF CURRENT AND POWER AVAILABLE FROM THE QUANTUM VACUUM

The available current and power from the background quantum vacuum electromagnetic radiation is derived here. I start with the energy density of electromagnetic modes in space, ρ(*hf*), given in Equation (1). Although the vacuum state has only virtual photons (Milonni, 2013), a naive calculation of the flux density of ZPE photons striking a surface can be carried out as follows. The flux is equal to the energy density divided by the photon energy, *hf*, times the velocity of photons, *c*. Just as with the usual Stefan Boltzmann law for blackbody radiation, a geometric factor of ¼ must be included. The photon flux per unit frequency is then:

$$j = \rho(hf)\frac{c}{4hf} \qquad (2)$$

To find the total flux available over a range of frequencies, the expression for ρ(*hf*) from Equation (1) is inserted into Equation (2), and the flux is integrated up to a cutoff frequency, *f*co. Keeping only the righthand bracketed ZPE term in Equation (1), *hf*/2, the total flux is:

$$\Delta J = \frac{\pi}{c^2}\int_0^{f_{co}} f^2 df = \frac{\pi}{3h^3c^2}(hf_{co})^3 \qquad (3)$$

This cumulative photon flux is substantial. For example, with a cutoff energy of 4 eV it is 1028 photons m^{-2} s^{-1}, corresponding to a photon current of 1.7 GA m^{-2}, where photon current is defined as the electrical current that would be produced if each incident photon generated the current from one electron.

To find the cumulative power available, the photon current at each energy in the integral in Equation (3) is multiplied by the photon energy:

$$P = \frac{\pi}{c^2}\int_0^{f_{co}} hf^3 df = \frac{\pi}{4h^3c^2}(hf_{co})^4 \qquad (4)$$

For the same 4 eV cutoff, the available power is 5.0 GW m^{-2}.

APPENDIX II: TESTS FOR ARTIFACTS

An extensive discussion of much of the investigation of artifacts is presented by Moddel et al. (2021a), except where noted with other references below.

One question is whether the results we see are just a short-term effect due to charging of interfaces or chemical reactions. To test for that, we continuously measured the current output over 4 hours, and later over 24 hours, to see if it declined. For example, if there were one charge trapped at each insulator molecule, they could produce the observed current for 3 µs. We found no change in the output, even over 24 hours. What we observe is not a transient effect.

If what we observe is due to harvesting of current over the active area of the device, as opposed to energy coming from another part of the circuit, the current should scale with device area. We found that the current scaled with area for areas extending from 6 to 10,000 µm^2. Similarly, the output should scale with number of devices in an array. We found that two different types of 4 x 4 arrays produce 4 times the current and 4 times the voltage of individual devices, showing the expected scaling.

Another question is whether the output is genuinely due to the adjoining optical cavity or might be the result of the way the MIM structure was processed after it was formed in order to produce the adjoining cavity. We measured devices at three different stages in the fabrication up through the deposition of the transparent dielectric in the cavity and found no output current; only when we deposited the final mirror layer did the power production appear. The output is not due to a quirk in the processing, but is instead produced only in the completed device.

There are several ways that the observed power output might inadvertently be due to pickup of charge or electromagnetic fields:

- To determine whether the current might be due to charge on the mirror that leaked through to the MIM structure, we compared the resistance of the optical cavity to that of the MIM device. For each optical cavity thickness we found that the cavity resistance was a least one million times higher than that of the MIM structure, so that any charge that inadvertently formed on the mirror could not leak through to the MIM region, through which the current is measured (see Figure 3(a)).
- Recently, we checked whether a voltage applied to the mirror might somehow create a field effect that induced current through the MIM structure. For mirror voltages up to 10 V, we found no effect on the MIM current (Weerakkody, unpublished 2022).
- To check for electromagnetic pickup we measured the I(V) characteristics of a device in a mu-metal box, which blocks low frequencies, and in an aluminum box, which blocks higher frequencies, and found no change from devices measured in ambient conditions.

Thermoelectric voltages, i.e., voltages due to temperature differences in locations on a device or in a measurement system, plague low-power measurements. Three different tests were carried out to test for possible thermoelectric voltages between the device and the measurement system:

- To compensate for such voltages, most measurements were carried out using a voltage reversal method as follows: two measurements were carried out with currents of opposite polarity, i.e., one when the base electrode was grounded and another when the upper electrode was grounded, and then the difference in the currents was subtracted to yield the final value.
- The fact that the 4 x 4 arrays discussed above yield four times the voltage output of a single device indicates that this voltage is not due to thermoelectric voltages between the device and the measure-

ment system, which would not scale with number of devices in series.

- Recently preliminary measurements were carried out as the device temperature was reduced from approximately room temperature (300 K) to approximately 80 K, and only small changes, within experimental error, were observed in the device output (Weerakkody, unpublished 2022).

To test whether the results could be due to temperature gradients within the sample, we carried out two tests:

- The temperature difference between the environment above the devices and the measurement stage was varied, and no change in the output was observed.
- Devices were measured inside a closed cryostat at a rigorously maintained uniform temperature, and the output was unchanged (Weerakkody, unpublished 2022).

For the reasons given, it appears unlikely that any thermoelectric effect is producing the results that we observe.

Calculations of the expected current resulting from absorption of known fluxes of cosmic rays and of solar neutrinos could not produce the currents that we observed.

In summary, we have examined all the potential artifacts that we and outside critics have suggested might be the source for the observed power production from our devices, and none can explain the results.

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ESSAY

Greedy, Blind, and Stupid—And Not Especially Quick Either

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SUBMITTED July 6, 2022
ACCEPTED August 21, 2022
PUBLISHED October 22, 2022

https://doi.org/10.31275/20222689

HIGHLIGHTS

The second law is exposed to be the 'Forrest Gump' and 'Gordon Gekko' of physical principles—but without a Hollywood ending.

INTRODUCTION

Sometimes Nature seems to have personality. One of its core traits, for instance, might be *economy*, as embodied in the *principle of least action*, a foundational idea for both classical and quantum physics. It appears *logical* and *aesthetic*, as shown by its beautifully interlocking laws and mathematical structure. Perhaps Nature is *amoral*, *indifferent to suffering*—maybe even *cruel*—as demonstrated through *natural selection*. When it comes to personal hygiene, however, there's no question: Nature is a slob. Sure, it produces examples of exquisite order (e.g., the symmetry of crystals, the intricate biochemistry of life), but beneath it all, supporting it, there's disorder and chaos everywhere, especially at the molecular level. There's even a law to enable this molecular malfeasance: the second law of thermodynamics. Nature's microscopic messiness is so widespread and universal, so overwhelmingly manifest in almost every action and system that the second law is often called the *supreme law of Nature*. There's no way to escape it, no means to undercut it, no scheme to bend, break, foil, or flummox it. Until now. This special issue of *JSE* is devoted to such systems. For insight into why the second law can be violated, let's look at it anthropomorphically, a tactic often used by scientists to describe and understand Nature intuitively, like one would an old friend. What are the second law's characteristics, propensities, and habits that set it up for failure? (After all, *character is fate*.) The short answer is this: The second law is greedy, blind, and stupid—and not especially quick either. This might seem flippant, but it's true. Let's unpack it.

Greedy

Like the oft-vilified (and sometimes admired) "corporate psychopath" Gordon Gekko in the movie *Wall Street*, with his signature line, "Greed is good," the second law is also greedy when it comes to entropy. Within the constraints imposed by the more foundational laws like conservation of energy, linear and angular momentum, charge, and within the physical limits set by local boundary conditions (e.g., walls, doors, membranes), the second law strives to maximize the entropy in any situation as fast as it can, like a flash trader who lives on short-term gains. The bigger the mess, the better. It just can't help itself.

It's a matter of probabilities. Consider a deck of cards, ordered by standard number and suit. This can be considered (arbitrarily) to be its state of least entropy (least disorder). Any rearrangement of the deck will only increase the deck's entropy. After the deck is shuffled a few times, it almost always ends up more disorganized, that is, less like the original, unshuffled deck. There are no new or special forces at play to make this happen, no conspiracy, no forethought, no malice or planning that goes into this; rather, it's simply a matter of probability: The deck changes its configuration with each shuffling, and there are far more ways for it become more disorganized than for it to become organized, therefore, probability favors disorder. That's it, mindless mayhem.

The condition at which a system's entropy is maximized is called thermodynamic equilibrium. (Distinctions between thermal, diffusive, and mechanical equilibria will not be made here.) Once a system arrives there, it is highly improbable—to the point of being effectively impossible—for it to leave that equilibrium state by itself because there are astronomically more microscopic configurations associated with its high-entropy equilibrium than there are low-entropy states out of equilibrium. The only way to get to a more ordered state involves the use of energy to push it away from equilibrium, but the use of energy generates more entropy. To be clear, almost every macroscopic process generates entropy and any attempt to reduce it by tidying things up inevitably generates more entropy. It's a no-win scenario, a thermodynamic Kobayashi Maru. Anthropomorphically, it's because the second law is greedy for entropy and just can't help itself.

This entropic greediness is quite dependable and, while it seems to guarantee the law's success, it also makes it predictable. This predictability, however, can be a liability under the right circumstances, an Achilles heel, because it's a hidden form of order that can be exploited by clever devices to undermine it. After all, if you can predict an opponent's behavior you have a better chance of defeating him. As Sun Tzu wrote in *The Art of War*, "If you know the enemy and know yourself, you need not fear the result of a hundred battles."

Thus, what is often regarded as the second law's highest virtue, its predictability—indeed, the attribute that elevates it to a law rather than just a handy rule of thumb—potentially holds a key to its own undoing. So, maybe greed is good sometimes, but not always. In the end, it wasn't great for Gordon Gekko—he went to jail—and, likewise, it isn't great for the second law either—it gets broken—just like the Kobayahsi Maru test.

Blind

The second law doesn't apply to individual particles, it's a collective law. The inexorable increase of disorder, ending at an equilibrium state of maximum entropy, emerges through the interactions of many individual particles acting independently. The second law can't be seen in the behavior of a single molecule any more than an ant colony can be understood by watching a single ant. Indeed, analogously to how tens of thousands of ants acting independently can form a highly organized antly society, the independent motions of sextillions of individual gas atoms can constitute a well-defined system called an *ideal gas*. The second law underwrites this: The gas fully fills its container, it uniformly spreads out, and quickly settles down to a uniform temperature, particle density, and pressure. This is the state of maximum possible entropy. The gas has extremely well-defined macroscopic properties, as exemplified by the ideal gas law (PV = NkT); however, no individual atom sees to this or even knows that it's part of the gas, or that it's governed by the second law. Likewise, the second law doesn't plan or understand what it's doing, nor can it see this outcome; it simply *does*. The second law is blind.

How blind? To get an idea, consider the following hypothetical scenario. Imagine a 10,000-megaton thermonuclear bomb. (This might be hard to imagine given that the largest bomb ever detonated, the USSR's Tsar Bomba, was 'only' about 60 megatons—yet still 3000 times more powerful than the ones that obliterated Hiroshima and Nagasaki—but in fact, the father of the US H-bomb, Edward Teller, did imagine building a 10,000-megaton thermonuclear bomb. Fortunately, no one else thought it was such a great idea.) Now let's say someone has their trembling finger poised a few microns over the bomb's detonation button—and let's hope it's not Edward Teller. The detonation of this 10,000-megaton thermonuclear bomb would certainly generate a hell of a lot of entropy—enough to truly overjoy some versions of the second law, while annihilating an area the size of Southern California—and all it would take would be for there to be a very slight fluctuation, a nearly imperceptual twitch of one little finger, to bring this about, perhaps just a few extra ions crossing an ion channel controlling a single muscle fiber. The potential entropy production hanging upon this tiny twitch is tremendous, but the second law is incapable of conceiving of it or affecting it. Instead, it just dithers about, making sure the air molecules around the finger are well mixed. This is because the second law cannot see more than one molecular collision ahead, one molecular vibration or energy transfer beyond where it currently is; it's fumbling about in the dark.

In summary, the second law is blind and cannot see the possibilities beyond the immediate, local microscopic domain of individual molecules. And it doesn't even bother to look. Flaw number two.

Stupid

The second law is dumber than a bag full of hammers—and Forrest Gump is its hero. It's so dumb that sometimes it's hard to tell whether it's being willfully ignorant, blind, or just plain stupid. (See H-bomb example above.) What is meant in this context, however, is that the second law has no memory, no ability to learn from mistakes, and no capacity to plan for the future. It lives and acts in the *eternal now*, which means that it can be tricked again and again—and again and again—by the same simple ruse. It never learns. As my mother used to say: *Fool me once, shame on you; fool me twice, shame on me*. Considering the second law's memory, this becomes: *Fool me once, shame on you. Fool me once, shame on you. Fool me once, shame on you. . . .* If thermodynamics were a chess game, the second law would be a player who moves his pieces about randomly, making a mess of the board, never plotting a strategy, never looking ahead or behind. Sure, for mindless molecular mayhem the second law can't be beat, but in organized games—like ones intelligent beings such as ourselves might cook up—the second law plays at a disadvantage. For us thermodynamicists, it's a matter of finding those games.

The second law's flaws—that it's dependably and predictably greedy for entropy production, that it can't see what it's doing, doesn't know what it's doing, can't remember what it's done, and can't plan what to do next—open the door to its manipulation and makes it an easy mark for scheming thermodynamicists.[1]

Not Especially Quick Either

Topping this off and making violations possible, the second law has another useful characteristic: It's not very quick. By this is meant not that it's stupid—we already know that—but instead that by most physical standards the second law achieves its ends relatively slowly as compared with other physical laws. Consider, for example, conservation of energy, momentum, or electric charge. These quantities are conserved in every known microscopic process down to sub-nuclear levels, as well as by every macroscopic process up to at least the scale of galactic superclusters. Because they are conserved at the very smallest length scales, they are conserved down to the smallest time scales, too. Not so with the second law.

As we've learned, the second law is a collective law, it is manifested only through the interactions of many particles. These collections can involve countless particles—quintillions of times more than the number of all the grains of sand on all the beaches in the world—and be spread over vast distances. (For example, electrical systems can be thermodynamically connected over thousands of kilometers by copper wires, or stellar nurseries might come to equilibrium over many light years distances over millions of years.) What this means is that significant time (and distance) scales can sometimes be involved for full satisfaction of the law, during which time (and space) the system is not at equilibrium and, therefore, is potentially ripe to have a bit of its energy siphoned off by a fast secondary process. Thus, if one operates cleverly within these nonequilibrium time (and distance) windows, the second law can be cheated. (It's like setting a trap for an opponent in chess—a game the second law can never master because it has neither the mind nor inclination for it.) In effect, you can steal a bit of energy *before the devil knows you're there*. You pick the second law's pocket so fast that it doesn't know it happened. Given how blind it can be, it might not notice, and even if it does, so what? It would forget its loss instantly. Thus, you can go on to cheat it again and again with the same thermodynamic ruse.

Many of the second law challenges documented in this special issue of *JSE* take advantage of these flaws. It is my belief that there are countless other possible devices that might foil it by such means. What has held us back thus far has been our collective scientific timidity and lack of imagination.[2] But these things can change, as the second law itself teaches. Now that we're in the throes of the Anthropocene Era, the stakes have never been higher that they do.

Come, Watson, come! The game is afoot!

ACKNOWLEDGMENTS

The author thanks the anonymous reviewer for constructive criticisms. He is especially indebted to George Hathaway for his tireless and cheerful work as guest editor for this special issue and for his helpful suggestions about this text.

NOTES

[1] For example, most second law violators run in thermodynamic cycles, converting ambient heat into work. Because such a device consumes thermal energy (heat), it cools relative to its environment. But as the Clausius form of the law states, heat runs from hot to cold, therefore, the environment naturally supplies heat to a violator to keep it warm—and running. (This also maximizes entropy production.) To my knowledge, every violator relies heavily on the second law—right up to moment that it bamboozles it, and usually even after. Thus, with its thoughtless, blind, and forgetful greed, the second law abets its own undoing.

[2] Those who read between the lines might see that this essay is as much a critique of the scientific community as it is one of the second law.

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BOOK REVIEW

Rationality: What It Is, Why It Matters, Why It Seems Scarce by Steven Pinker

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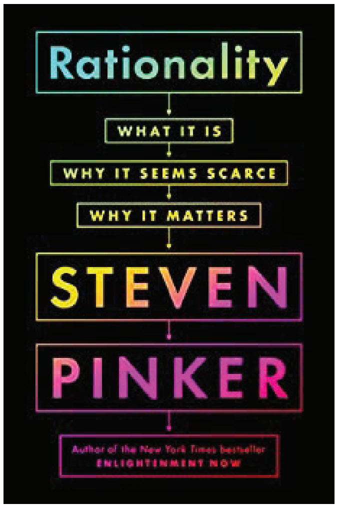

Viking, 2021
ISBN 978-0525561996

https://doi.org/10.31275/20222587

In his latest book, *Rationality: What It Is, Why It Matters, Why It Seems Scarce*, Steven Pinker brings attention to how we might strengthen our reasoning powers, as well be more cognizant of the ways we might fall short. This mostly takes the form of a wide-ranging tour, acquainting us with various forms of fallacious reasoning as well as tools to improve our reasoning faculties. As a famous professor of psychology at Harvard, Pinker is arguably well-equipped to provide a comprehensive survey on various sorts of cognitive biases and ways of thinking about rationality. The book provides a useful introduction on various tools and models that arguably characterize rational thinking. But as I'll discuss, despite his considerable knowledge and expository skills, he stumbles in areas where his own motivated reasoning clouds subject matter he is either attempting to explain or dismiss.

In the first chapter, he notes that while rationality often appears to be in short supply, he provides evidence for its universality even among hunter–gatherer tribes, with the San of southern Africa being his example. Here, Pinker demonstrates that many of the sophisticated hunting and decision techniques employed by the San suit their goals admirably. But then Pinker pivots toward areas where our reasoning could be flawed in the areas of math, logic, and probability, according to psychologists.[1] And he highlights that even experts in math or probability can succumb like the rest of us. How do we reconcile this with Pinker's observation of the sophisticated reasoning of hunter–gatherers? Pinker eventually gives us something of an answer toward the end of the book, where he explains that we do much better with the problems we face in our immediate surroundings (and where there are real stakes) than relatively more abstract and remote problems.

Pinker explains that rationality, essentially, is "a kit of cognitive tools that attain goals in particular worlds" (p. 5). Later, he puts it slightly differently as an "ability to use knowledge to attain goals" (p. 36). And for Pinker, knowledge is "justified true belief," or the things we know confidently that are grounded in facts. Of course, Pinker acknowledges that our quest for truth requires epistemic humility, as perfect rationality and purely objective truth must elude all humans. But we can nevertheless aim to be aware of various rules and models of reasoning that can aid us in avoiding biases that obstruct rationality, and "allow us to approach the truth collectively in ways that are impossible for any of us individually" (p. 41). Much of the book provides a tour of cognitive biases and tools for avoiding them.

One important area in this regard is logic and critical thinking. Here he provides an introduction into formal logic, as well as some peculiar outcomes or implications that can aid us in identifying fallacious arguments. His list of fallacious arguments includes the straw man, move the goal, begging the question, whataboutism, special pleading, and ad hominem arguments. But throughout the book, he also tends to take his subject matter as jumping off points for critical takes against favorite targets. In one case, he notes that advocates of ESP "can engage in special pleading, such as explaining that ESP fails in experimental tests because it is disrupted by the negative vibes of skeptics" (p. 87). But is this really a common tactic among psi advocates? Pinker cites no examples. A few pages later, he cautions against using argument from authority to justify shaky claims because, he notes, some scientists do have flaky beliefs, which include, according to Pinker, beliefs in telepathy, astrology, and synchronicity. Again, Pinker gives us no arguments or citations to justify the dubious nature of such beliefs, but in all likelihood his intended audience does not require them.

In another chapter, Pinker turns to our cognitive biases concerning probability and randomness. For instance, we (understandably) place greater weight on impressions based on our experienced frequencies of events, rather than on the actual data of such occurrences. Such instinctive impressions, he notes, distort our understanding whenever the strengths of those impressions don't accurately reflect the events. And outside of our experience, our view of the world is largely shaped by the media. But the media has incentives to highlight violence in our community or the likelihood of a terrorist attack. On the other hand, relatively peaceful events or even positive news are often filed under "not much happening" and therefore do not get reported. According to Pinker, "As the economist Max Roser points out, news sites could have run the headline 137,000 People Escaped Extreme Poverty Yesterday every day for the past twenty-five years" (p. 124). But they never run the headline, because there was never a particular day when it suddenly happened. Thus, he argues that one of the greatest developments in human history—a billion and a quarter people escaping from poverty—goes unreported.

Another aspect of probability that Pinker argues skews our reasoning is the tendency of finding patterns after the fact, which he labels post hoc fallacies. Thus, he dismisses the notion of synchronicity or meaningful coincidences, introduced by Carl Jung, by noting the likelihood that occasionally coincidences just simply happen. Now cultivating a cautious attitude toward taking patterns or otherwise random events to be more than they are seems like good advice. That said, some psychologists and philosophers remain intrigued by this and other notions of Jung's. And while something like synchronicity might be very difficult to test within a scientific framework, that difficulty does not by itself invalidate it.

Like his chapter on logic, much of the book explains how rationality is considered formally. Thus, he introduces us to rational choice theory and how economists might incorporate it into their frameworks. And he doesn't shy away from exploring how rational choice theory, while useful in some contexts, leads to peculiar outcomes in others. Pinker provides a serviceable introduction to statistical decision making, as well as the difficulty of applying such tools in the real world. In another chapter, Pinker introduces the reader to game theory as a tool for understanding rational decision making in different cases. Many of these various introductions will likely be useful, though perhaps tedious, to readers unfamiliar with the topics. Readers more familiar with rational choice and game theory may still find value in how Pinker employs such concepts to rationality (or the lack thereof) in our world.

In a chapter focused on causation and causality, Pinker presents several examples of how we are prone to see patterns or effects that are only apparent. One example he discusses is the tendency of 'regression to the mean.' Examples he lists include sports stars profiled in *Sports Illustrated* after an outstanding performance, but who follow up with a more average performance. Some have referred to this as the *Sports Illustrated* jinx, but Pinker argues that this is more likely a return to a relatively normal performance after an especially good one. Pinker notes that scientists are by no means immune from this regression to the mean. Occasionally a study finds an unusual effect, perhaps something too good to be true, that other authors have difficulty replicating. Pinker notes that regression to the mean is likely responsible for what many have termed the "decline effect." And once again, Pinker manages to jab some of his favorite targets. In his words,

> Many of our primitive intuitions of causal powers turn out, in the light of science, to be mistaken, such as the 'impetus' that the medievals thought was impressed upon moving objects, and the psi, qi, engrams, energy fields, homeopathic miasms, crystal powers, and other bumkum of alternative medicine. (p. 258)

Throughout his book, Pinker chooses to denigrate topics he considers fringe, flaky, or the product of defective reasoning, without much in the way of argument or citation. On these instances, readers more familiar with the literature on psi and other subjects will have reason to question Pinker's epistemological modesty. Taking psi in particular, there is considerable evidence that this data represents something real that we don't yet understand. Recently, Cardeña (2018) has summarized the meta-analyses of experimental analysis across an assortment of experimental designs, based on data that have been accumulated and pooled over decades. Pinker fails to mention this, although I believe it is quite likely that he is aware of Cardeña's (2018) summary findings.[2] This raises the question of whether Pinker's own cognitive biases are filtering out data that arguably merit a closer look.[3] I'll return to this question later.

Later in the book, in a chapter titled "What's Wrong with People?" Pinker focuses on the rise of misinformation and conspiracy theories in recent years. Why are people susceptible to various far-fetched, irrational, or plain crazy ideas? (Pinker casts a large net on what he judges to be crazy, with believers in reincarnation or extrasensory perception lumped together with anti-vaxxers and deniers of the Holocaust.) Pinker discusses how motivated reasoning, which involves driving an argument toward a favored conclusion that one prefers, plays a central role. For various reasons, people are motivated to embrace particular beliefs and will marshal their cognitive resources to arrive there, even at the cost of abandoning facts and optimal reasoning. People may seek out arguments that ratify beliefs they identify with and shield themselves from those that might disconfirm them.

Pinker describes some relevant studies that find individuals identifying with a political party will rapidly accept data that confirms their positions and will criticize more strongly statements opposed to their identified positions. One case focuses on how different political orientations might shape or filter what is seen on a video of a protest in front a building.[4] When the video was labeled as a protest against abortion at a health clinic, conservatives tended to see a peaceful demonstration, while liberals noticed various details such as protestors blocking the entrance and intimidating those trying to gain entry. When it was labeled as a protest against the exclusion of gays, conservatives saw the crowd as angry, while liberals viewed the protestors as relatively peaceful.

The rise in political tribalism is often blamed on social media (Facebook, Twitter, etc.), and this is arguably an important source. However, Pinker (and many others) argue that polarization on broadcast and cable news might be even more important. Additional factors Pinker adds to the list include regional polarization (with educated liberals locating in urban enclaves and less educated conservatives tending to live in rural areas) and the decline of class-crossing civil-society organizations like churches and volunteer groups.

Pinker also argues that universities have played a role in the growing decline of the public's trust in science, and this in turn contributes to the rise in misinformation. Pinker believes universities are culpable, primarily through their "suffocating left-wing monoculture, with its punishment of students and professors who question dogmatics on gender, race, culture, genetics, colonialism, and sexual identity and orientation" (p. 313). Pinker also adds that universities "have a responsibility to secure the credibility of science and scholarship by committing themselves to viewpoint diversity, free inquiry, critical thinking, and active open-mindedness" (p. 314).

But another possibility Pinker doesn't consider or discuss is the strong secularizing influence universities have on their students and society. And Pinker himself arguably presents the poster-perfect stereotype of the professor at an elite academic institution who dismisses any value in religion. For myself, I find Pinker's tendency to lump notions of God or teleology in with the sort of dubious beliefs found in today's conspiracy theories highly inappropriate. There is also evidence that spirituality and religion are linked with psychological health and well-being (Vieten & Lukoff, 2022).

I've skipped over an important chapter (Chapter 5), in which Pinker introduces his readers to the Bayesian framework for assessing evidence. Here Pinker mounts his strongest attack against psi, in particular Daryl Bem's findings on precognition. He begins with a straightforward introduction of Bayes's Rule and how we might assess questions of evidence given our prior beliefs (before we are presented with the evidence), posterior likelihoods (how we update the priors given the evidence), and the probability of the evidence itself. Much of the focus here is on how we formulate our prior probability, and how much faulty reasoning might be avoided through more skillful application. His opening example of finding the right prior is in the context of a medical diagnosis, where accurate data is plentiful. He shows that by using population data on the accuracy of medical diagnosis, we can formulate a prior that assists us in making sense of a favorable (or unfavorable) diagnosis.

Having established the importance of constructing an accurate prior based on the available data, Pinker seamlessly turns toward attacking Daryl Bem's findings in support of precognition. This involves a bit of sleight of hand; Pinker pivots from a medical case, where plentiful data exists, to an area where little data exists, except arguably that generated by psi researchers, which Pinker prefers to avoid. Pinker holds Daryl Bem's 2011 paper, "Feeling the Future: Experimental Evidence for Anomalous Retroactive Influences on Cognition and Affect," as a prime example where we do not sufficiently consider the correct prior, within a Bayesian framework. In his paper, Bem (2011) presented nine time-reversed versions of well-known psychological experiments, which allowed him to test for precognition, or whether test participants could "feel the future." But Pinker explains that accepting such results at face value is absurd, and thus we should weight our priors accordingly to discount such evidence. But how do we construct an appropriate prior to investigate this question? Toward this end, Pinker brings in David Hume's argument against accepting the evidence of a miracle. As

Pinker explains, a miracle necessarily requires that we apply a very small value to the prior probability in order to safeguard our accepting "pseudoscience." Therefore, a large amount of evidence in favor of what Pinker assures us is a dubious finding is required to overcome the necessarily small assignment of value to the prior. Pinker explains that using Bayes' Rule this way is just another way of applying Carl Sagan's maxim (which appears at the beginning of the chapter): "Extraordinary claims require extraordinary evidence." And Pinker notes that as we might expect, Bem's findings have failed to be replicated.

Many people reading this chapter (who have little knowledge of the psi literature) will likely come away thinking that Bem's findings have not held up under the weight of serious examination and that researchers have turned away from such shenanigans. But on the contrary, the meta-analysis on Bem's "feel the future"-style experiments have confirmed strongly significant effects (Bem et al., 2015).[5] In other words, the efforts to duplicate Bem's experiments ended up vindicating Bem's findings.[6] Like Cardeña's (2018) summary of the evidence on laboratory psi, Pinker does not inform his readers of this information. How do we account for this poor characterization of the data in a book whose ostensible aim is to keep our cognitive biases in check? Could Pinker be deliberately trying to present a one-sided view, or is he genuinely ignorant of the evidence?

I'd like to press on this issue of how Pinker manages to treat this (admittedly controversial) subject in a couple of ways. First, like many skeptics of the psi data, Pinker has arguably misread Hume's essay "Of Miracles."[7] Hume's argument was aimed at the undependable nature of human testimony regarding religious miracles described in religious scripture. Examples Hume mentioned included the dead rising from their graves, severed limbs growing back, and the blind being cured by spittle. For Hume, testimony on religious matters was inherently unreliable, dependent on reports for events in remote areas, with relatively few witnesses. He noted that we might expect testimony on a religious marvel to excite emotions of passion and wonder. Simply lifting Hume's argument against miracles found in religious testimony and applying it against anomalous findings under controlled test conditions, with the aim of replicability, appears to be inappropriate, to say the least.

Pinker believes that Hume's argument allows him to frame the question of accepting something like precognition as: "Which is more likely[,] that the laws of the universe as we understand them are false, or that some guy got something wrong?" (pp. 158–159). Setting aside his mischaracterization of this literature (as if it were based only on "some guy" in a lab), we can note that Pinker never considers the possibility that the psi data reflects something about the gaps in our current understanding of the world. Anomalous findings in scientific history, which initially clashed with conventional theories and assumptions, have played an important role in advancing scientific theory. We can't simply assume that science is pretty much done and there aren't any future surprises in store, no matter how successful current science appears to be. As it happens, the psi data arguably falls into domains, such as consciousness and quantum mechanics, where our understanding remains incomplete. By ignoring the possibility that the data suggests something about the gaps in our current theories, Pinker (and his fellow skeptics) argue for an astronomically low value for the prior, based on their view that psi should be treated as a supernatural miracle.[8]

Pinker may be aware of the problem that our understanding remains incomplete, but he avoids any deeper reflection on this. In his book, he recounts that a colleague once suggested "Maybe Pinker doesn't understand the laws of physics?" Pinker's reply was "But actual physicists, like Sean Carroll in his [2017] book *The Big Picture*, have explained why the laws of physics really do rule out precognition and other forms of ESP" (p. 160).[9] Carroll, the physicist Pinker chooses to cite here is a well-known cosmologist who also aims for wide audiences in his books. In citing Carroll (recall Pinker earlier cautioned against argument from authority with respect to "fringe" science), he fails to mention that Carroll is also well-known for advocating the Everett (Many Worlds) interpretation of quantum mechanics. This interpretation posits that that the universe is constantly branching and forming additional universes parallel to ours. So far, no ability to test this claim appears on the horizon. So here we have Pinker, not particularly worried about the wide disagreements on interpretations of quantum mechanics, reaching out to find an agreeable ally but at the cost of arguably turning Sagan's maxim of "extraordinary claims" on its head.[10]

For me, all of this is a rather impressive display by Pinker, a world-famous expert on human reasoning and its limitations, inadvertently putting his own prejudices in the display window. And Pinker provides good support to characterize it as such. As he explains toward the book's end, "The mustering of rhetorical resources to drive an argument toward a favored conclusion is called motivated reasoning" (p. 288). Just a bit later, he discusses how the motivated reasoner likely filters how information is consumed: "In biased assimilation (or selective exposure), people seek out arguments that ratify their beliefs and shield themselves from those that might disconfirm them" (p. 290). Needless to say, presenting this understanding in the book and applying such guidance on one's own beliefs are two very different things.

Fortunately for Pinker, few among his audience are likely to be familiar with the psi literature and in probability many share his prejudices. Those more knowledgeable or sympathetic to the data are perhaps written off, having drunk the Kool-Aid, so to speak. But unfortunately, because of Pinker's large influence, his skewed portrayal of psi (as well as other topics he views as "fringe") may prevail.

While Pinker's book does possess virtues in its clear accessibility on a wide range of aspects on rationality, his unreliability as a guide on his central subject matter—cognitive bias—substantially mars the book's value. A rather sobering take-away is that a world-class psychologist can stumble against his own cognitive biases while at the same time lecturing in top professorial mode on the nature of such biases. But thinking more positively, perhaps the book serves as a useful case study that illustrates the difficulty of acquiring and distributing new knowledge of the world in the face of entrenched assumptions and beliefs which even the most well-informed and "reasonable" among us have embraced.

NOTES

[1] Pinker goes into some depth describing three problems psychologists have used to uncover fallacious reasoning: the Cognitive Reflection test, the Wason selection test, and the Monty Hall problem.

[2] Cardeña's (2018) summary on the meta-analyses on laboratory psi was published in *American Psychologist*, the flagship journal of the American Psychology Association.

[3] On Pinker's dismissal of psi and lack of curiosity on the evidence, see also a recent post by Rupert Sheldrake (2021). https://unherd.com/2021/11/rationalists-are-wrong-about-telepathy/

[4] Kahan et al., 2012.

[5] The subsequent meta-analysis was based on 90 experiments from 33 laboratories in 14 countries. The overall statistic for this combined data was $z = 6.40$, with a $p = 1.2 \times 10^{-10}$. This strong statistical significance was also robust to Bayesian analysis.

[6] Roe (2022) presents a good overview of Bem's original paper, criticisms, and the meta-analysis on findings.

[7] "Of Miracles" is found in Hume's *An Enquiry Concerning Human Understanding* (2007).

[8] See also Wagenmakers et al. (2011) who attacked Bem's (2011) findings using a similar argument for constructing an extremely low prior within a Bayesian framework.

[9] See Nobel laureate Brian Josephson's (2022) critical response to both Pinker and Carroll. https://opensciences.org/comments-on-steven-pinker-s-view-of-the-paranormal.

[10] My intention here is not to criticize the Everett Many Worlds interpretation. While I am not an advocate, I accept that some find the interpretation attractive for philosophical reasons. That said, I do not understand how someone simultaneously argues: 1) extraordinary claims require extraordinary evidence and 2) the Many Worlds interpretation, for which we have no evidence, is likely the best explanation for the quantum measurement problem.

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Scientific
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BOOK REVIEW

On the Fringe: Where Science Meets Pseudoscience by Michael D. Gordin

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Oxford University Press, 2021
ISBN 978-0197555767

https://doi.org/10.31275/20222449

ESSAY BOOK REVIEW

SPEAKING OF "PSEUDO-SCIENCE" ENTAILS SCIENTISM: THE IMPORTANCE OF NOT BEING EARNEST ABOUT SCIENCE

Context

In contemporary society, "science" signifies authoritative understanding of the natural world; therefore "pseudo"-science means claimed but *in*authentic, *false* knowledge about nature; and "fringe" science, between those two, means doubtfully trustworthy knowledge.

In any case, whether or not it is a conscious decision and whether or not it is admitted, attributing authoritative understanding to science entails accepting the religion of scientism, the belief that scientific knowledge is superior to any other claims of knowledge.

But the content of "science" is created by human beings. Once it is conceded that science is fallible, as all human activities are bound to be, it becomes clear that any mainstream "scientific consensus" is also fallible; and therefore heterodox claims of knowledge should be greeted, initially at least, with a degree of tolerance and a willingness to consider evidence, to seek objective facts before judging something to be false knowledge, or, in contemporary jargon, "fake news."

The subtitle of this essay was inspired by the life (and work) of Oscar Wilde, who was only one among an uncountable host of human beings who have suffered seriously from the intolerance of their fellow human beings, the intolerance of the societies in which they lived. The intolerance Wilde faced may have had nothing directly to do with science, but it did indirectly: Declaring and believing his sexual preferences to be "unnatural" and therefore abhorrent presumed, with great dogmatic earnestness, that we command authentic knowledge about what is natural.

All forms of intolerance are rooted in the belief that one's opinions are unquestionably, absolutely true. But that sort of certainty belongs only to the God who created the universe and everything in it—if, of course He or She actually exists. And even if They actually exist, human beings are incapable of knowing for sure His or Her mind. That quite a number of people have claimed to know the mind of God is anything but convincing or reassuring: The stark and vigorous disagreements among those would-be Prophets is rather sound proof that their various claims are ill-founded.

So it behooves human beings to display a certain degree of tolerance for the views of those who disagree with them, and a sense of humor would be a welcome corollary, one which never seems to partner with intolerance.

The evil that intolerance can bring was described, for me most cogently, by Jacob Bronowski (1973, p. 186), as he mused at a pond near the remains of the crematorium at the Nazi concentration camp at Auschwitz:

> Into this pond were flushed the ashes of some four million people. And that was not done by gas. It was done by dogma. It was done by arrogance. It was done by ignorance. When people believe that they have absolute knowledge, with no test in reality, this is how they behave. This is what men do when they aspire to the knowledge of gods.

Nowadays the belief that one's views are based on unquestionably true knowledge is held not only by some adherents of God-type religions but also by huge numbers of people who take "science" as the touchstone and guarantor of certain knowledge. In other words, adherents to scientism. One indication of this reliance on science, of making science into the religion of scientism, is the use of epithets like "fringe science" or "pseudo-science" to label anything that one wants to discredit and denigrate. "Junk science" is even more emphatic, as is the currently popular label of "denialism," a yet more passionately applied criticism, often intended to imply base motivation as well as unwarranted refusal to accept the truth offered by science.

The book under review reveals its implicit scientism most clearly in its discussion of "denialism," but it is also evident in how it handles the various examples of what the author calls and what gets labelled as pseudo-science.

As to denialism, the book's "key reference" (p. 109) is *Merchants of Doubt* (Oreskes & Conway, 2010), which argues that nefarious, politically right-wing institutions and scientists, together with commercial interests, notably energy and tobacco companies, deliberately try to create doubt where there should be none, for instance about the reality of human-caused global warming or the deleterious health consequences of smoking cigarettes.

In terms of objective evidence, however, there is indeed uncertainty—doubt—on each of those issues. The mainstream belief in both cases is based on statistical data, and statistical analysis is inherently incapable of delivering 100% certainty, the "yes-or-no" certainty sometimes attainable in physics or chemistry when dealing with not-too-complicated systems. "Statistically significant" merely means a certain probability of being right, with a cut-off that is arbitrary, and typically, in social science and medicine, quite weak at 95% ($p \leq 0.05$). Asserting that a statistically significant result must be accepted as true, like claiming that objective criteria enable the ability to distinguish "science" from imposters, amounts to "conjuring certainty where there is none" (Bauer, 2014).

As for global warming and climate change, innumerable books, articles, websites, and blogs have presented evidence over the last several decades that human activities are *not* the chief culprit. For the most recent and authoritative work pointing out that alarmist rhetoric and cherry-picked numbers greatly exaggerate the present impact of human activities on climate, see *Unsettled* (Koonin, 2021), whose main points are cited in a recent review (Bauer, 2021a).

As for health consequences of smoking cigarettes, it is not being questioned that smoking cigarettes is not good for health; I do believe that inhaling tobacco (or any other) smoke is unhealthy.[1] But it is also possible to exaggerate the degree of risk and the specific type of risk associated with smoking. For example, the dangers of second-hand tobacco smoke have been unreasonably hyped (Kabat, 2008, ch. 6); and the common shibboleth that "smoking causes lung cancer" is misleading[2]: because in common usage, "A causes B" implies *always*, that A is sufficient to cause B, not that A is one among a number of "risk factors" for B to occur. However, "only" about 10–20% of smokers contract lung cancer,[3] smoking is just one among a number of factors capable of increasing the risk of lung cancer.

A common tactic in (ab)using statistics is to cite misleading data. About 80–90% of lung cancers are indeed found in smokers, but that does not specify the risk of lung cancer in those who smoke: About 80–90% of smokers *do not* get lung cancer. So the bald statement "smoking causes lung cancer" is misleading; perhaps even as *deliberately* misleading as the *creation* of doubt excoriated by Oreskes and Conway (2010).

The misapplication of percentages in this sort of reverse way is a common stratagem, an illustration of "how to lie with statistics" (Huff, 1954; see also Best, 2001, 2004). I. J. Good (1995, 1996) illustrated that nicely in connection with publicity about the notorious trial of O. J. Simpson: Should a wife-battering ex-husband be the most likely suspect if his former wife was murdered? A crucial distinction has to be made between two questions easily confused. First: How likely is it that a jealous former husband with history of wife abuse *will murder* his former wife? Second: *Once a woman has been murdered*, whose former husband had battered her, how likely is it that the former husband is the murderer? The probability in the first case is quite low—most wives who have had a battering husband are never murdered by them. But in the second case the probability is reasonably high.

It would certainly have been quite appropriate for *Merchants of Doubt* to point out that commercial interests like the tobacco industry, as well as socially and politically conservative groups and individuals, seek to over-emphasize uncertainty without giving the other side appropriate due, but they had no need to *create* uncertainty.

Even the most devoted groupies of science will admit, if pressed and in the abstract, that science is not always absolutely right—even as, *in any particular case*, they insist that it is not to be questioned; for instances of this, take the self-styled "Skeptics," accurately described by Marcello Truzzi (1987) as *pseudo*skeptics.

Pseudo-skeptical faith in the absolute trustworthiness of science is often said to be justified by the purported fact that science is self-correcting and that it is guarded from error by application of the scientific method. However, the scientific method is more myth than actual practice (Bauer, 1992, 2017), and if self-correction is ever called for it means that what was earlier promulgated was incorrect. Any contemporary pronouncement of what science knows or understands is therefore subject to an irreducible degree of uncertainty because it cannot yet be known whether this is a case of error just awaiting future self-correction.

At any rate, detailed reasons for doubting the "science" of harm from smoking and about global warming have been set out above. Dismissing those evidence-based reasons without explaining what is wrong with them is an illustration of pervasive, if implicit, scientism.

In *On the Fringe*, implicit scientism may be most obvious in the discussion of denialism, but it is also discernible in the sections on particular instances of fringe science or pseudo-science, for they all assume that the mainstream view is correct, an approach facilitated by a rather large number of substantive errors.

Disclosures

Any book that promises insights about the relationships among science, fringe science, and pseudoscience is surely of prime interest to anomalists and scientific explorers. But what to do if it is a bad book? That is, if its proffered insights are spurious, misguided, misleading, or plain wrong?

Perhaps it would best be ignored. But this particular bad book happens to have been published by Oxford University Press, an academic as well as commercial publisher of long-standing high repute, and the book's author is a distinguished historian at Princeton University. Moreover, the dust jacket offers a positive comment from an eminent philosopher of science, and several published reviews of the book are positive.[4] Amazon readers rated it 4.2/5, but with an unusually high proportion of negative written reviews: three negatives and only two positive. At goodreads.com the rating was 3.7/5.

Details of what is wrong in this book are set out below, but first the biases of this reviewer need to be disclosed. Gordin and I had exchanged e-mails a decade ago after I had written quite a positive review (Bauer, 2013) of his earlier book, *The Pseudoscience Wars* (Gordin, 2012). So I was looking forward to reading his new book on a topic central to my interests for a long time, and which I had written about long ago (Bauer, 2001). I was then enormously disappointed as well as astonished that this new book is so flawed. I admire historians in general for the characteristic depth and holistic character of their work, and Gordin's *The Pseudoscience Wars* fits that bill quite well, whereas *On the Fringe* is shallow and poorly researched, and where it is not superficial it is muddle-headed or plain wrong.

Content Overview

An eight-page Preface is followed by Chapter 1, "The Demarcation Problem," about how to distinguish science from other matters. Without an objective criterion, pseudoscience would not be definable or distinguishable from real science. For philosophers, the issue traces back at least to classical Greece: how to distinguish true knowledge from mere opinion?

Contemporary confusion and floundering about "pseudo-science" comes about because the conventional wisdom now equates "science" with "(assumed true) knowledge." Philosophers may still see the demarcation problem as how to distinguish true knowledge from false, but pragmatists point out that "science" cannot stand for true knowledge since "science" comprises a host of disparate human enterprises—physics, psychology, biology, etc.—doing different things in different ways, studying a huge variety of matters (Bauer, 1992, 2017) with no logical or practical common thread other than the semantic one of labeling them all as "science."

Gordin properly agrees with Laudan (1983) that no "bright line" demarcation like Popper's falsifiability withstands scrutiny; in other words, there is no objective, logical criterion for what is science and what is not. That ought to end the matter; but then the waters are muddied by the suggestion that "more dimensions that corresponded to the heterogeneity of scientific practice" might work (p. 12).

Fringe doctrines are then grouped into four categories: vestigial, hyper-politicized, counter-establishment, and supernatural (positing extraordinary powers of mind). Chapter 2 is about the Vestigial Sciences, citing astrology and alchemy. Chapter 3 is about Hyper-politicized Sciences, for example, Aryan Physics, Lysenkoism in the Soviet

Union, and eugenics. Within the Counter-establishment (Chapter 4) the book mentions phrenology, creationism, cryptozoology, cosmic catastrophism, extraterrestrial aliens on Earth including UFOs, and Flat-Earth theories. Chapter 5, "Mind Over Matter," discusses mesmerism, Spiritualism, and "University Parapsychology."

Chapter 6 acknowledges in its heading that "Controversy is Inevitable." It discusses polywater, water memory, cold fusion, and "Fraud and the Replication Crisis." Chapter 7 has the puzzling[5] heading, "The Russian Questions," which turn out to be "Who is to blame?" and "What is to be done?" It includes a section on "Denialism" and concludes that "the only way to eliminate pseudoscience is to get rid of science, and nobody wants that" (p. 101).

Finally, there are lists for further reading: Astrology, Alchemy, Science and National Socialism, Eugenics and the Racial Science, Phrenology, Creationism, Cryptozoology, Ufology, Flat Earth, Mesmerism, Spiritualism, "ESP and Debunking," "Polywater, water memory, and cold fusion," "Fraud and the replication crisis," and Denialism.

Criticisms

"Tackling pseudoscience focuses on the problem of what counts as truth" (p. viii). Yet in the rest of the book this criterion is not applied, perhaps because of the book's already cited final conclusion, "the only way to eliminate pseudoscience is to get rid of science." Indeed, because the only workable definition of "pseudo-science" is that the scientific mainstream "consensus" has so labeled it.

"Pseudo" equals pretending to be what it is not. If "science" is not a manifestly definable object whose definition is for all intents and purposes settled and agreed, as indeed it is not (Bauer, 1992, 2017; Laudan, 1983), then "pseudo-science" has no settled and agreed meaning either. "Pseudo-science" is simply an epithet deployed by those who want to discredit something, *period*. There is no other common thread among the examples cited in this book, or for that matter, wherever else the term is used. Semantics-based confusion is everywhere, including throughout this book. Its title implies that "Fringe" is a border between science and pseudo-science, yet vestigial sciences, just (p. 14) described as among *fringe* doctrines, are then referred to as *pseudo*-sciences (p. 15).

The inadequacy of this book's attempted grouping into four categories is illustrated in a number of ways, most comprehensively because all the examples separated here into four categories could fit into just one: counter-establishment. It is the Establishment, the mainstream consensus, that underlies all the labeling of things that are *not* mainstream as "pseudo" (bad) or "fringe" (not really good). Thus the topics included under "hyper-politicized sciences" are certainly counter to what the global contemporary mainstream consensus holds. Again, it is not obvious why eugenics is not grouped among vestigial sciences, since it was regarded as proper science in the first decades of the 20th century. Flat-Earth theories, too, surely ought to have been among the "vestigial." The book itself says "Most pseudosciences are vestigial" (p. 27). But the "vestigial" category is almost a priori unsuitable since science itself, as well as all the topics labeled (at some time or other) pseudo or fringe, are not unchanging entities; all of them have changed over time to greater or lesser degrees.

"Creationism" could surely have been included in the "Mind over Matter" group since it is no less supernaturally motivated than is "Spiritualism," unless one would like to include it too under "vestigial," where it would fit quite well; indeed, it could be viewed as an earlier incarnation of "intelligent design."

In other words, the book's classification of specific examples of pseudo-science into these four categories is muddled, ambiguous, self-contradicting; it provides no useful insights.

Again, when discussing the demarcation problem, the book cites approvingly as a "local criterion" (p. 13) the label of "pathological science" coined by Irving Langmuir for the cases of N-rays and extrasensory perception; yet elsewhere the book includes extrasensory perception in the "Mind over Matter" category. Langmuir didn't get it right, by the way, in labeling N-rays as somehow pathological instead of simply an understandable if sad mistake made by a distinguished scientist who happened to be fallible, as human beings are, even the most distinguished and accomplished among us.

Gordin's earlier book, *The Pseudoscience Wars*, had focused explicitly on the *social context* of the arguments over "pseudo-science," ignoring as a criterion whether the substantive claims happen to be true. But that is not done in the present book, and it could hardly work here since the social contexts of the particular topics discussed have no commonality. In the earlier book, focusing heavily on the Velikovsky Affair (Bauer, 1984), the context was specifically the intellectual milieu in the United States soon after World War II. But the topics mentioned in this recent book share no common social or even chronological or geographic context. All they share is denigration by the mainstream establishment.

So the book offers no insights into general issues concerning topics on the fringe, or those totally outside the mainstream scientific community and out of keeping with the conventional wisdom about science. Sadly, the discussions of individual topics is also superficial, less than illuminating, and sometimes simply wrong.

Thus it is far from clear what one learns from the assertion that astrology held a position in early modern Europe "analogous to economics in the early twenty-first century" because it was so empirically and mathematically grounded and was criticized for its assumptions and failing predictions (p. 17). Is there warrant here for designating contemporary economics a pseudo-science?

It is also bemusing to read that "The problem with the Nazi and Soviet cases is not that the science was 'political' or even 'politicized'—climate science and knowledge of reproductive health are often politicized today"—as though politicizing science could ever be acceptable. Unless science is impartial and disinterested, it cannot properly serve society and its policymakers.

As to the Soviet Union, the claim that "Lysenkoism was atypical" because the Soviet Union "heavily invested in science" confuses apples with oranges. In point of fact, other sciences were also corrupted there on political grounds, for instance the then-modern theory of chemical bonding was banned as contrary to dialectical materialism.

Regarding cryptozoology, to suggest that Bigfoot matters were *not* monetized or otherwise exploited (pp. 51–2) ignores the doings of Erik Beckjord and his California "museum" in the Trancas Restaurant in Malibu, and the widely publicized Patterson-Gimlin film. That funding was not forthcoming for sonar or submarine searches at Loch Ness (p. 52) would surely mislead readers: Mini-subs were nevertheless deployed more than once (Mackal, 1976: ch. IV, 305–6), and there have been dozens of sonar searches with strikingly positive results, recording echoes from large moving objects, often at considerable depths (Bauer, 1986, pp. 25, 90, 140, 162; Mackal, 1976, ch. IX, App. E).

It is again misleading to credit Immanuel Velikovsky with "some successes in predicting unusual properties of Venus and Jupiter" (p. 53). His basis for the predictions was the fanciful scenario that Venus was hot because it was once a comet-like body ejected from Jupiter; but "hot" is hardly a meaningful term here—"hot" compared to what? (Bauer, 1984, pp. 18–19, 47–48, 86–87, 161, 260, 270).

Few, if any, mainstream researchers would agree with this book that "parapsychological findings have had a profound impact on the methodology of experiment that has reshaped mainstream research . . . [and] pushed psychology to ever greater sophistication in both the laboratory and in data analysis" (p. 60). And few would agree that the commission of 1874 investigating Mesmer's claims initiated "a tradition in parapsychology that continues to the present" (p. 63). Equally plucked from some imaginary world is the assertion that those investigations represented "the introduction of randomization into experimental trials," which "soon migrated from the murky domains of parapsychology to become perhaps the most important change in experimental practice of the last two centuries" (p. 66). A well-known founding guru of statistical analysis, R. A. Fisher, had introduced the protocol of randomization in 1925 (Hall, 2007).

A more trivial error is describing the Committee for Scientific Investigation of the Paranormal (CSICOP) as a "commission" (p. 72). And Brian Josephson is hardly "the most prominent name in the parapsychology community at present" (p. 73). He is certainly referred to because his Nobel Prize in physics is thought by some naïve groupies of parapsychology to lend respectability to their interest, but much more cited within the parapsychology community is the enormous body of work published by the PEAR group at Princeton University under the leadership of Robert Jahn.

The notion that "one of the triggers for what has come to be called the 'replication crisis' in psychology" was an article by Daryl Bem (p. 74) is a novel suggestion indeed. The lack of reproducibility of results that are based on statistical analysis, most prominently in the social sciences, had been pointed to and deplored long before and besides Bem's article. The actual crisis is the failure of so much published work to be subjected to the test of replicability, owing to pressures to publish as well as incompetent peer-reviewing and journal-editing (Ritchie, 2020, p. 34 & *passim*).

Here, as also when discussing "denialism," the book seems to view anything that is not mainstream as thereby faulty, thereby displaying the author's no doubt unconscious obeisance to scientism. For instance, the phrase "Rhine-style statistics" (p. 74) is derogatory innuendo implying that J. B. Rhine's statistics were faulty. However, while Rhine's work can be and has been criticized for experimental protocols that may not have guarded well enough against cheating, there was nothing wrong with his statistical calculations. Similarly speculative innuendo is directed at Pons and Fleischmann for their claim of "cold fusion," that "they stage-managed the announcement to heighten the effect" (p. 84). The reality was that the administration of their university, learning that Steven Jones[6] at Brigham Young University was planning to make public a similar claim, decided to hold a press conference; Pons and Fleischmann have testified that they would have preferred to wait until their already-in-press article had been published. Nor were Pons and Fleischmann "disgraced, and both moved to France in 1992" (p. 85); they moved there because Toyota, the Japanese auto manufacturer, enabled a well-funded laboratory for them there. In 2012 it was reported[7] that Mitsubishi and Toyota were continuing to fund research into "low-energy nuclear reactions" (LENR), the label that has replaced "cold fusion." Yet this book asserts that the original findings were "an experimental artifact (like polywater), experimental overinterpretation (like water memory), or deliberate fraud" (p. 85); although it then backtracks (p. 86) by admitting that "the death of cold fusion has been greatly exaggerated." What is a reader to make of this? Or that "some, but not all, cold-fusion researchers are labeled today" as "pseudoscientists"? The book has given no clear definition of "pseudoscientist," naturally enough since it has given no clear definition of "pseudoscience" other than giving examples of some topics so labeled; presumably then a person who is actively pursuing a topic that is pseudoscience would be a pseudoscientist. So why only "some"?

It is this sort of thing that causes me to describe this book as "muddled."

A brief reference to peer review on p. 88 is in the context of articles failing the replication test but managing to get published. Much more would need to be said here if it were to offer useful insight into the role of peer review in connection with fringe science and pseudo-science.

The concluding Chapter 7 states that pseudo-sciences abound now as they always have. Of course they do, since they are the same as holding a minority view opposed to official doctrine or mainstream consensus. But having said that, what insights does the book offer? What *could* it offer? Presumably, critical discussion of particular cases labeled pseudo-science, but the cursory treatment given specific cases in this book is inadequate, as illustrated for some of them in the criticisms made above. The dubious familiarity with each topic is exemplified also by the statement that "the tiny scale at which the strings ostensibly operate leaves the [string] theory largely inaccessible to empirical confirmation" (p. 91); it is not the tiny scale that hampers empirical test, it is the enormous energies that would be required for actual experiments.

As to what distinguishes cranks or pseudo-scientists from proper scientists (p. 92), the book would have done better to cite Jack Good (1998): Geniuses are cranks who happen to be right, and cranks are geniuses who happen to be wrong.

Denialists are said to "engage in a common set of behaviors and share personal connections that render the designation reflective of a sociological reality" (pp. 92–93). I would be interested personally in what those commonalities are supposed to be, given that I have been called an HIV/AIDS denialist as well as a climate-change denialist. And yet I was quite unaware that my "strategy of denialism" was created by the "public relations firm . . . Hill and Knowlton" in 1954 (p. 93). Of course, "once you understand how the denialist strategy works . . . the particular label matters less" (p. 95). Does not recognizing the strategy depend on first applying the label?

Antagonism to vaccination is lumped with denialism, and suffers the same problem of over-generalizing, for instance that "Anti-vaxx bases its position" on Andrew Wakefield's claims (p. 97). But it is only a small proportion of "anti-vaxxers" who are against *all* vaccination; some, like me, recognize that HPV vaccines, for example, do cause harm (Reiss, 2017) in exchange for no proven benefit. Perhaps that is why "A distinctive feature of anti-vaxx as compared to other fringe movements is the prominence of women in its ranks" (p. 98)—HPV vaccines were introduced, after all, to prevent cervical cancer, whose occurrence is only in women. But then the book muddles again by conceding that women were also prominent in Spiritualism. Indeed; it was actually originated by women, as were Christian Science, theosophy, and the aquatic-ape theory of human evolution.

The superficiality, the lack of depth of these discussions may be explainable by the absurdly small and unrepresentative items listed as "Further Reading."

Regarding astrology, sorely missing is Michel Gauquelin,[8] whose astrology-like statistical correlations ("the Mars effect") stimulated a reaction that led to the founding of CSICOP. Also deserving mention here is Suitbert Ertel,[9] who continued along the same lines as Gauquelin.

As to creationism, all the titles are by debunkers, while missing are works by the founder of modern creationism, Henry Morris, or by other proponents; or anything about the "scientific" version, "intelligent design."

Under cryptozoology, it is simply wrong to assert that the "literature . . . is divided into case studies by creature" (p. 107). Bernard Heuvelmans, founder and pioneer of cryptozoology, published books covering a wide range of "unknown" animals,[10] as did Roy Mackal,[11] and as Karl Shuker continues to do,[12] and then there are the compendiums by George Eberhart[13] and Loren Coleman.[14]

For ufology, only a journal article is listed. Yet there are encyclopedias[15] as well as innumerable books that anyone interested in the topic ought to be aware of. For "Polywater, water memory, and cold fusion," once again only debunking sources are cited. "Fraud and the replication crisis" ought surely to have mentioned Broad and Wade's *Betrayers of the Truth: Fraud and Deceit in the Halls of Science* (1982), which first brought attention to the increasing frequency of dishonesty in modern science. Stuart Ritchie's (2020) *Science Fictions*, a necessary reference here, may have appeared too recently for this book to mention it. All the titles under "Denialism" are by people (instances of Truzzi's *pseudoskeptics*) who presume that the mainstream consensus is always right.

There should also surely have been some further reading on the general topic of the book, for example, Martin Gardner (1957), whom Gordin had rightly characterized in his earlier book as "the writer who probably did more than anyone else in the post-war period to turn discussions of alleged pseudoscience into debunking crusades" (Gordin, 2012, p. 12).

Recommendation

The book should not be recommended to anyone who wants to learn about the scope and nature of science, fringe science, or pseudo-science. Anyone who reads this book ought to be made aware also of the criticisms set out above.

A very general moral is that whenever matters of public policy are at issue, it would be wise to consider minority views, not merely the contemporary mainstream scientific "consensus" (Bauer, 2021b).

NOTES

[1] It is a major regret that I ever took up smoking, albeit I did so at a time when "everyone" was smoking and when "most doctors prefer[ed] Camels," when it was polite to offer your cigarette-pack or cigarette-case for others to share when you felt like having a smoke. Fortunately, having *not* smoked for three decades now, it seems that the earlier decades of smoking caused me no identifiable long-term harm.

[2] Oreskes and Conway (2010) acknowledge some of the caveats set out here, but they make such bald statements as "Tobacco caused cancer. That was a fact" (p. 14).

[3] For instance, https://www.medicinenet.com/what_percentage_of_smokers_get_lung_cancer/article.htm; https://www.verywellhealth.com/what-percentage-of-smokers-get-lung-cancer-2248868#toc-lifetime-risk-by-smoking-status; https://www.reuters.com/article/us-cancer-lung-nutrients-sb/nutrients-may-be-why-some-smokers-avoid-cancer-idUSTRE65E5JW20100616

[4] https://www.theguardian.com/books/2021/jun/02/on-the-fringe-by-michael-d-gordin-review-why-pseudoscience-is-here-to-stay
"A fascinating exploration of the line between science and pseudoscience takes in anti-vaxxers, ufology and spoon-bending physicists at the CIA" https://www.publishersweekly.com/978-0-19-755576-7
"This will be helpful to anyone curious about how to separate the wheat of science from the chaff of pseudoscience." https://www.sciencenews.org/article/on-the-fringe-book-science-pseudoscience
"In his latest book, historian Michael Gordin shows how hard it is to define pseudoscience."

[5] The questions are said to be Russian because they are "the titles of (not very good) nineteenth-century Russian novels: Alexander Herzen's *Who Is to Blame?*, published in 1845–1846, and Nikolai Chernyshevsky's *What Is to Be Done?*, published in 1863. (The latter title was also used by Vladimir Lenin for a political treatise in 1902)" (p. 90). That illustrates that the book's author is an historian specializing in matters Russian, but it is hardly relevant to fringe science or pseudo-science.

[6] The book directs derogatory innuendo also against Steven Jones (p. 86).

[7] Steven B. Krivit, "Mitsubishi reports Toyota replication," 7 December 2012
http://news.newenergytimes.net/2012/12/06/mitsubishi-reports-toyota-replication; "Toyota and Mitsubishi collaborate on new LENR research in Japan"
https://energycatalyzer3.com/news/toyota-and-mitsubishi-collaborate-on-new-lenr-research-in-japan

[8] Gauquelin's many books include *L'influence des astres* (1955), *The Cosmic Clocks* (1967), *The Scientific Basis of Astrology* (1969), *Astrology and Science* (1970), and *Cosmic Influences on Human Behavior* (1973).

[9] *The Tenacious Mars Effect* (1996).

[10] Notably *On the Track of Unknown Animals* (original French ed., 1955; latest English ed., 1995).

[11] *Searching for Hidden Animals: An Inquiry into Zoological Mysteries* (1980).

[12] Many books are listed at http://www.karlshuker.com/books.htm, for instance *Extraordinary Animals Worldwide* (1991), *In Search of Prehistoric Survivors: Do Giant 'Extinct' Creatures Still Exist?* (1995), *The New Zoo: New and Rediscovered Animals of the Twentieth Century* (2002).

[13] *Mysterious Creatures: A Guide to Cryptozoology* (2002, two volumes).

[14] *Cryptozoology A to Z* (1999, with Jerome Clark).

[15] By Jerome Clark (3rd ed. 2018); an earlier encyclopedia was by William Birnes (2004).

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FUNDING FOR SCIENTIFIC RESEARCH

2022/2023

FUNDAÇÃO
Bial
Institution of public utility

With the aim of encouraging research into the healthy human being, both from the physical and spiritual point of view and particularly in fields largely still unexplored but which warrant further scientific analysis, BIAL Foundation now opens a new call of its Grants Programme for Scientific Research with the following characteristics:

1. Scope and purpose - Only the fields of Psychophysiology and Parapsychology shall be covered by this Programme. The goals to be met by the applicants shall be set out by the Research Project under application.

2. Addressees - All scientific researchers will be admitted as applicants, either individually or in groups, except those working for BIAL Foundation or for any of the companies belonging to BIAL Group. The current Grant Holders (principal investigator or co-principal investigator) of BIAL Foundation can also be admitted as applicants; however, they shall only benefit from new grants under this Programme after the successful completion of the work comprised in the scope of previous awarded grants.

3. Duration and commencement - The total duration of the grants under the Program shall not exceed 3 years and shall commence between 1st of January and 31st of October 2023.

4. Total amount and payment's periodicity - The approved applications shall benefit from grants with a total amount up to €60.000 (sixty thousand euros). The specific amount shall be fixed at BIAL Foundation's sole discretion in accordance with the needs of the Research Project under application.
The amount awarded to each Research Project shall be understood as a maximum amount, which shall be paid by BIAL Foundation upon verification of the documents of expenses submitted, under the terms of the Regulation.
The payments shall be made annually or bi-annually. This periodicity shall be defined in accordance with the schedule of the Research Project.

5. Applications - Applications should be submitted in English no later than 31st of August 2022, in accordance with the Regulation of Grants for Scientific Research of BIAL Foundation, via specific online application form available at www.fundacaobial.com. Applications regarding the following projects will not be considered eligible:
a) Projects from Clinical or Experimental Models of Human Disease and Therapy;
b) Projects whose main scope is eating behaviour, sexual behaviour, physical exercise or fundamental neuroscience.

6. Assessment of applications and notification of decision - Applications shall be assessed by the Scientific Board of BIAL Foundation. The decision shall be disclosed, by notice to the applicants, within 4 (four) months from the final deadline for submission of applications.

7. Applicable Regulation - The submission of an application implies and means the full acceptance by the applicant of the terms and conditions set out in this announcement and in the Regulation of Grants for Scientific Research of BIAL Foundation, which governs the present call.

BIAL Foundation reserves the right to refuse the application of former Grant Holders who have repeatedly violated their legal and contractual obligations with BIAL Foundation.

The Regulation of Grants for Scientific Research of the BIAL Foundation is available at:

Fundação BIAL
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Tel. + 351 22 986 6150 • www.fundacaobial.com • fundacao@bial.com

BICS
Bigelow Institute for Consciousness Studies

Up to $1 Million in Funding for Research into the Survival of Human Consciousness After Death
The 2023 Bigelow Institute for Consciousness Studies Grants Program: "The Challenge"

After a massive international response judged by a panel of outstanding experts, the 2021 Bigelow Institute for Consciousness Studies (BICS) essay contest ("The Contest") established that there is evidence beyond reasonable doubt for the survival of consciousness after permanent physical death ("life after death," or "the afterlife"). Building on that success, the 2023 BICS Challenge will fund research into contact and communication with post-mortem or discarnate consciousness leading to the reception of higher order information of benefit to humankind with the allocation of a grand total of up to $1 million in grants.

Up to $50,000 will be awarded to 12 projects and up to $100,000 will be awarded to a further 4 projects, exclusively in the field of the survival of consciousness after death. (BICS reserves the right to determine the value of each project and the final amount awarded.)

As a general guide, historical examples of such contact and communication with "the afterlife" have included: Emanuel Swedenborg; Allan Kardec; William Stainton Moses; Edgar Cayce; and Jane Roberts.

Historically, the methods used have been wide-ranging, including, but not limited to, automatic writing, dreams, visions, veridical hallucination, trance, hypnosis, direct voice, mental mediumship, physical mediumship, so-called spirit boards, instrumental transcommunication (ITC), etc.

Applicants are free to decide on their approach, but projects must address the hypothesis that valid higher order information, generally classed as "wisdom," can be received in communication with post-mortem or discarnate consciousness through the use of robust methodologies.

In the first instance, applicants should submit a **preliminary proposal** with professional bio, or bios of all team members, showing their qualifications and experience in this field ("the survival of human consciousness after death"). Individual applicants may apply. In addition, BICS encourages researchers to form teams or consortia, ideally, but not necessarily, with a host entity.

Preliminary proposals should be precise and succinct, and include an abstract, a thorough budget breakdown showing how payment instalments will be tied to research deliverables ("milestones") over the course of the project, and a clear demonstration that the project design is novel and will stand up to academic scrutiny.

Preliminary proposals are invited from November 1st, 2022, to January 1st, 2023, with selected applicants being invited to submit full proposals from January 1st, 2023, to April 1st, 2023. Grants awarded will run from August 1st, 2023, to May 1st, 2024 (9 months).

Preference will be given to new and innovative studies. BICS will not enter into discussion or "coaching" of proposed projects. Further terms and conditions can be found at bigelowinstitute.org.

Submit a preliminary proposal from Nov. 1st, 2022, until Jan. 1st, 2023, to Dr Colm Kelleher at info@bigelowinstitute.org. Submissions will be considered and approved on a rolling basis, therefore applicants should submit as early as possible.

Journal of **Scientific Exploration**
Anomalistics and Frontier Science

SOCIETY
FOR
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EXPLORATION

CALL FOR PAPERS

Special Issue of the Journal of Scientific Exploration
in collaboration with the
Journal of the Society for Psychical Research

"THE DARKER SIDE OF SPIRITUALITY"

Special Issue Co-Editors: Malcolm Schofield, Chris Howard, & Carrie Childs
Deadline for submission: January 31st, 2023
Next Steps: Submit a 200-word Abstract of your proposed contribution to:
editor@scientificexploration.org

Introduction:

Spirituality is often studied, modeled, or discussed in terms of efficacious emotions and experiences. But religio-cultural beliefs and behaviors—and the quest for power, knowledge, or transcendence—can sometimes take darker paths. This thematic issue thus explores current thinking and research in this general domain to gain a more balanced appreciation for consciousness and the broad array of emotions, cognitions, and motivations that define the human condition.

Article Types:

- Quantitative or Qualitative Research
- Important Case Studies or Multiple Studies
- Systematic or Scoping Literature Reviews
- Brief Reports
- Conceptual Works & Essays
- Book Reviews of Topical Literature or Media

Possible Research Topics:

- Personality and the spectrum of supernatural behaviors
- Modern occultism: Psychology of curses, hexes, spells, and talismans
- Energy "vampires"
- Demonic possession
- Stigmata phenomena
- Negative NDEs or Psi Experiences
- Spirit Cleaning Rituals and Outcomes

Journal of **Scientific Exploration**
Anomalistics and Frontier Science

JSE Author Guidelines — Updated January 2022
Submit to *journalofscientificexploration.org*

JSE publishes Regular Articles, Literature Reviews, Brief Reports, Book Reviews, Essays, and Letters/Correspondence. Invited content in these categories is also published periodically. Please ensure that your submission meets APA Guidelines (7th edition) and conforms to the parameters below.

There are **no strict word limits**, but guidelines for different types of submissions are given below. In all cases, authors should be as clear, direct, and concise as possible. The Editor-in-Chief reserves the right to mandate revisions to the lengths of accepted papers in the interest of readability, accessibility, and space.

Contributions can be empirical research, critical or integrative reviews of the literature, position papers, policy perspectives, and comments and criticism. Studies can adopt diverse methods, including qualitative, ethnographic, historical, survey, philosophical, case study, quantitative, experimental, quasi-experimental, data mining, and data analytics approaches.

A. **Regular Articles** (~12K words max). Primary research or interesting and important theoretical papers that foster the diversity and debate inherent to the scientific process. This entails novel or innovative ideas that have some 'fragmentary' experimental or empirical support that can be evaluated with logic and open-mindedness to present academia with provocative hypotheses that might be rejected by other more conventional journals.

   - All empirical results that have not been replicated should be called 'preliminary' with the findings treated as such. Peer-review and publication priority will be given to studies that are (a) pre-registered or (b) replications. Note that 'replication' can involve repeating the research procedure in a (nearly) identical separate study to be reported within the same paper (e.g., 'Study 2: Replication'). Or, large datasets can be divided randomly into 'Training' and 'Test (or Validation)' sets, i.e., the research findings are those results that replicated in the Test set.

   - To promote stricter transparency and context for readers, all analyses where appropriate should provide effect size statistics in the form of direct percentages of either association (correlative analysis) or mean percentage differences (ANOVA, t-tests, etc.). In the case of correlative analysis, reported results shall report R^2 to provide a covariance percentage estimate. Mean tests shall provide a 'percentage change' indicating the actual percentage change between groups (e.g., M = 3.44 Group 1 versus M = 4.02, in Group 2, on a five-point scale is calculated by the following: ABS $[M_1 - M_{2/5}$ (scale range)$]$ = 11.6% shift or change in means). Standard effect statistics also are allowed, so long as the above percentage techniques are likewise reported. These statistics should be reported in results as 'percentage effect' and follow immediately after standard statistical analysis notation. For correlation, (r = .43, p < .01, percentage effect = 18%), for means tests (M_1 = 3.44 versus M_2 = 4.02, t = 3.443, p < .01, percentage effect = 11.6%).

B. **Systematic, Narrative, and Scoping Reviews** (~13K words max). All meta-analyses and systematic reviews should include a PRISMA flow diagram to clarify for readers how the exclusion/inclusion criteria were applied to create the literature set under consideration: See http://www.prisma-statement.org/

C. **Brief Reports**—Rapid Publications (~2K words max). These are usually pilot studies, direct or conceptual replication attempts of previous work, case studies, brief evaluations, reviews, or 'citizen scientist' efforts that are unique, first-time reports, with no more than two tables and/or figures and 10 references. This rapid publication option is especially appropriate for graduate-level student studies, pilot or preliminary research, or descriptions of important new methods or instrumentation. These reports are subject to blinded peer review in the same manner as research articles. Authors should follow all requirements for longer manuscripts when submitting Brief Reports, including that they have not been submitted or published elsewhere.

D. **Book Reviews** (~2K words max). Structured for readability and utility in which the content is suitably contextualized and includes links to general model-building or theory-formation in the respective domain(s). Please use the following headers, or otherwise incorporate these themes into the review: Author Disclosures; Content Overview; Pros, Cons, and the Book's Contributions to the Literature; Recommendation; and References (if applicable). For an example, see: https://www.spr.ac.uk/book-review/poltergeist-night-side-physics-keith-linder

E. **Essays** (~8K words max). Important conceptual or philosophical commentaries, observations, or arguments to spark constructive discussion or debate relative to theory, methodology, or practice.

F. **Letters/Correspondence/Commentary** (~1K words max). Must address substantive issues relative to recently published content in the Journal.

Submissions (A) to (C), and (E) as appropriate, must also include the following sections:

- **Lay Summary / Highlights** (~50 words max). Placed at the beginning of the article before the scientific abstract, this is a short—1 to 3 sentences—bottom-line assessment of the value of the paper. Avoid technical terms and prepare the comments akin to a published quote to a non-specialist or uninformed journalist or student about the researchers' interpretation of the main results.
- **Implications and Applications** (~150 words max). Placed immediately after the Discussion section to succinctly summarize or suggest how the study's methods or findings can potentially inform the study of other issues, anomalies, fields of study, including interdisciplinary and multidisciplinary approaches.
- **Author Contributions** (Contributor Roles Taxonomy). Please include this subsection under the Acknowledgments section. Follow standard guidelines such as this one from Elsevier: https://www.elsevier.com/authors/policies-and-guidelines/credit-author-statement. Also, please include ORCID numbers for authors where possible.
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