

Portland State University

PDXScholar

Mathematics and Statistics Faculty
Publications and Presentations

Fariborz Maseeh Department of Mathematics
and Statistics

7-2018

Reconsidering the Foundations of Thermodynamics from an Engineering Perspective

Terry Bristol
Portland State University

Follow this and additional works at: https://pdxscholar.library.pdx.edu/mth_fac



Part of the [Engineering Commons](#), and the [Physical Sciences and Mathematics Commons](#)

Let us know how access to this document benefits you.

Citation Details

Bristol, T. Reconsidering the Foundations of Thermodynamics from an Engineering Perspective. Preprints 2018, 2018070139 (doi: 10.20944/preprints201807.0139.v1).

This Pre-Print is brought to you for free and open access. It has been accepted for inclusion in Mathematics and Statistics Faculty Publications and Presentations by an authorized administrator of PDXScholar. For more information, please contact pdxscholar@pdx.edu.

1 Article

2 **Reconsidering the Foundations of Thermodynamics** 3 **from an Engineering Perspective**

4 **Terry Bristol**

5 Institute for Science Engineering and Public Policy, Portland State University; bristol@isepp.org

6 Received: date; Accepted: date; Published: date

7 **Abstract:** Currently, there are two approaches to the foundations of thermodynamics. One,
8 associated with the mechanistical Clausius-Boltzmann tradition, is favored by the physics
9 community. The other, associated with the post-mechanical Carnot tradition, is favored by the
10 engineering community. The bold hypothesis is that the conceptual foundation of engineering
11 thermodynamics is the more comprehensive. Therefore, contrary to the dominant consensus,
12 engineering thermodynamics (ET) represents the true foundation of thermodynamics. The
13 foundational issue is crucial to a number of unresolved current and historical issues in
14 thermodynamic theory and practice. ET formally explains the limited successes of the 'rational
15 mechanical' approaches as idealizing special cases. Thermodynamic phenomena are uniquely
16 dissymmetric and can never be completely understood in terms of symmetry-based mechanical
17 concepts. Consequently, ET understands thermodynamic phenomena in new way, in terms of the
18 post-mechanical formulation of action. The ET concept of action and the action framework trace
19 back to Maupertuis's Principle of Least Action, both clarified in the engineering worldview research
20 program of Lazare and Sadi Carnot. Despite the intervening Lagrangian 'mechanical idealization of
21 action', the original dualistic, indeterminate engineering understanding of action, somewhat
22 unexpectedly, re-emerged in Planck's quantum of action. The link between engineering
23 thermodynamics and quantum theory is not spurious and each of our current formulations helps
24 us develop our understanding of the other. Both the ET and quantum theory understandings of
25 thermodynamic phenomena, as essentially dissymmetric (viz. embracing complementary), entail
26 that there must be an irreducible, cumulative historical, qualitatively emergent, aspect of reality.

27 **Keywords:** Foundations of thermodynamics; Boltzmann vs. Carnot; engineering thermodynamics;
28 quantum thermodynamics; Principle of Least Action; complementarity; Maupertuis; Lazare Carnot
29

30 **1. Introduction**

31 Historically, there were two paths to thermodynamics: the engineering path of Sadi Carnot and
32 the mechanical path of Clausius and Boltzmann. Oxford's Peter Atkins, in his book, *The Second Law*,
33 maintains: "The aims adopted and the attitudes struck by Carnot and Boltzmann epitomize
34 thermodynamics. ... Carnot traveled toward thermodynamics from the direction of the engine, then
35 the symbol of industrial society: his aim was to improve its efficiency. ... Boltzmann traveled to
36 thermodynamics from the atom, the symbol of emerging scientific fundamentalism, his aim was to
37 increase our comprehension of the world at the deepest levels then conceived [1]."

38 Despite many unanswered questions, the modern consensus at least in the physics community,
39 favors Boltzmann's mechanistic formulation of thermodynamics and the corresponding historical
40 narrative of development of thermodynamics. Sadi Carnot and the caloric theory are presented as
41 'mere' historical footnotes. That is how I was taught thermodynamics in my physics and chemistry
42 education at UC Berkeley. And yet to my surprise Atkins adds: "Thermodynamics still has both
43 aspects, and reflects complementary aims, attitudes, and applications [1]."

44 I confess that it took me a full three years of digging into the foundations to convince myself that
45 not only was Atkins correct about the history, but that, in actual practice, there are indeed, two
46 distinct modern formulations of thermodynamics. One typically favored in the physics community,
47 the other in the engineering community. As a rough initial characterization, the former uses a closed
48 system paradigm and the latter uses an open system paradigm (viz. hot source-working system-cold
49 sink). The Clausius-Boltzmann paradigm embraces the concept of entropy and the objectivity of the
50 standard Four Laws [2]. The engineering paradigm identified with Sadi Carnot is often identified
51 with the limit of efficiency and the Carnot cycle.

52 Discussing Atkins's two formulations theme with a colleague, Robert Ulanowicz, he offered:
53 "Oh, yes! When completing my Ph.D. in chemical engineering at Johns Hopkins, in my orals, in
54 response to the obligatory thermodynamics question, if I had answered in terms of the Boltzmann
55 paradigm, I would have been on the street the next day looking for a job selling real estate."

56 In convincing myself of Atkins's historical thesis and the continuing modern separation in
57 current practice, I also discovered to my satisfaction that the two resulting formulations are not
58 compatible. The crucial foundational question then presents itself: what is the relationship between
59 mechanical thermodynamics and engineering thermodynamics? Atkins suggests that they are
60 complementary, and I can see that in a certain sense, the open-closed difference makes this plausible.
61 At the very least neither one is reducible to the other. The differences suggest a difference of type, a
62 qualitative conceptual difference. They appear to be logico-mathematically incommensurable.

63 Certainly, the dominant representation of thermodynamics that comes from the physics and
64 philosophy of physics community favors the Clausius-Boltzmann formulation [3][4][5]. In history of
65 science scholarship, the engineering thermodynamics tradition is frequently represented as based on
66 misconceptions, such as the caloric theory. And although key features of the open systems model are
67 taught, such as limit of efficiency and the Carnot cycle, there is a presumption that engines are not
68 fundamental or foundational and are somehow reducible to their component particles and to closed
69 system mechanics.

70 I came to thermodynamics from physics, later expanding my perspective in philosophy of
71 science. In the Popperian tradition of bold hypotheses [6], my thesis here is that: engineering
72 thermodynamics, properly understood, is more general and more fundamental than mechanical
73 thermodynamics. According to this thesis, all the mechanical formulations of thermodynamics must
74 involve idealizations making them special cases of limited validity within the more general
75 engineering framework. The bold hypothesis entails that engineering thermodynamics is
76 foundational, formally subsuming and superseding all possible mechanical formulations. It is
77 important to be clear that I understand 'science' as 'mechanics', and all mechanical frameworks as
78 defined by classical presupposition of symmetry and conservation. An entailment of the bold
79 hypothesis is that these symmetry and conservation principles must be limited, based on
80 idealizations.

81 Atkins further maintains that the empirical research that discovered and defined
82 thermodynamic phenomena as 'real', and, per hypothesis, as not reducible to the classical mechanical
83 phenomena, in effect, discovered a fundamental, post-mechanical dissymmetry in the nature of
84 reality [1].¹

85 2. Approach and Methods: Subsume and Supersede

86 To claim that one theory subsumes another means that all the successes of the subsumed theory
87 can be accounted for by the more general subsuming theory [7]. However, the subsumed theory is
88 'not even wrong'. A simple analogy illustrates. For instance, the flat earth theory worked quite well,

¹ Atkins (page9) [1]: "The Second Law recognizes that there is a fundamental dissymmetry in Nature: the rest of this book is focused on that dissymmetry, and so we shall say little of it here. All around us, though, are aspects of the dissymmetry: hot objects cool, but cool objects do not spontaneously become hot; a bouncing ball comes to rest, but the stationary ball does not spontaneously begin to bounce."

89 apparently for millennia. The advanced spherical earth theory is more general and accounts for all
90 the successes of the flat earth theory. The historical reasonableness of the flat earth theory is pointed
91 out in that we are very small observers on a very large sphere. The flat earth theory still works quite
92 well within certain boundary conditions. However, the more general, subsuming, advanced spherical
93 earth theory does not include the falsity content and predictions of the flat earth theory, such as falling
94 off the edge of the earth at some point. Similarly, NASA's Apollo mission to land on the Moon
95 programmed their computers using Newtonian physics even though it was presumed that
96 Newtonian physics is subsumed by the more advanced Relativistic physics. For the Apollo mission,
97 the nine-mile correction suggested by relativistic effects was well within the practical uncertainty of
98 the positions resulting from each rocket-burn.

99 In the later developments of quantum theory Bohr offered a formal criterion of proper
100 succession, what he called The Correspondence Principle: the later, more general theory must be able
101 to account for the successes of the earlier theories without including their falsity content [8].

102 To claim that one theory supersedes another is more subtle and conceptual [7]. The transition to
103 a more general, superseding theory is conceptually discontinuous, meaning that you cannot simply
104 reason your way from the initial theory to the superseding theory. You cannot derive the more
105 general superseding conceptual system from the superseded theory. The conceptual discontinuity
106 entails the logical discontinuity. In his seminal book, *The Structure of Scientific Revolutions*, physicist
107 and historian of physics, Thomas Kuhn, highlighted the conceptual discontinuity that characterized
108 advances in knowledge and understanding [10]. Kuhn appropriately branded major advances as
109 'revolutionary' and, as involving a paradigm shift in both concepts and experimental techniques. The
110 advanced, superseding theory adopts a qualitatively distinct, conceptually novel, framework. The
111 successes of the previous theories are subsumed, albeit understood, conceptually, in a new way.
112 Characteristic of advanced conceptual tools is that they allow one to generate novel questions,
113 qualitatively new types of questions that were inconceivable in the previous, limited conceptual
114 framework. Again, by analogy, in the spherical earth theory one can imagine new types of exploration
115 and investigation such as circumnavigation and launching artificial satellites. The range of
116 meaningful inquiry expands – emerges qualitatively. ²

117 Per hypothesis, engineering thermodynamics subsumes and supersedes all possible mechanical
118 representations of thermodynamics. Kuhn's paradigm shifts are represented as from one scientific
119 theory to a more general scientific theory, always remaining *within* an overall scientific (mechanical)
120 framework, defined by some sort of symmetry and conservation principles. The paradigm shift to
121 the engineering thermodynamic framework is a step more general. As the flat earth is understood as
122 a limited idealization from within the spherical earth theory, the symmetry and conservation
123 principles definitive of all possible mechanical worldviews are to be understood as limited
124 idealizations from within the more general understanding of the engineering thermodynamic
125 framework.

126 An important consequence of the conceptual advances involved in paradigm shifts is that just
127 as one cannot logically derive, for instance, Einstein's relativistic physics from Newtonian physics, it
128 is also the case that one cannot understand the conceptual apparatus of Einstein's relativistic physics
129 from within the conceptual framework of Newtonian physics. Similarly, the more sophisticated post-
130 mechanical conceptual framework of quantum theory cannot be either derived from or understood
131 from within the conceptual frameworks of either Newtonian particle mechanics or Maxwellian
132 electromagnetic wave mechanics.

133 The point of all this is that according to my bold hypothesis the conceptual apparatus of the
134 engineering framework cannot be derived from or understood in terms of any classical mechanical
135 conceptual framework. Stated another way, the concepts of the more advanced engineering

² This emergent aspect of actual advances remains largely unexplained. In the idealized scientific (mechanical) model, advances should be systematic, logico-mathematically consistent and convergence toward complete knowledge, wherein the range of meaningful questions should narrow as the uncertainty declines.

136 thermodynamics framework, by their very nature, are not reducible to, or properly understood in
137 terms of, classical scientific, mechanical concepts.

138 An illustrative consequence, in the recent philosophy of engineering literature, is offered by
139 Stanford aeronautical engineer, Walter Vincenti, in his seminal book, *What Engineers Know and How
140 they Know It* [11]. He argues that engineering knowledge is conceptually distinct from scientific
141 knowledge. Concerning the common representation of engineering as ‘applied science’, Vincenti
142 responds: “Engineers know from experience that this is untrue.” Vincenti challenges us to develop a
143 more general epistemology that is not, by its very nature, reducible to any possible classically
144 scientific, mechanical epistemology.

145 Duke engineer, Henry Petroski, in his book, *The Essential Engineer*, argues that what we have
146 previously imagined to be scientific inquiry and scientific knowledge, is only properly understood,
147 from within a more general superseding engineering framework as engineering inquiry and
148 engineering knowledge [12].

149 Per hypothesis, engineering knowledge and engineering activity, by their very nature, can only
150 be properly understood within the more general, foundational, engineering thermodynamic
151 framework. In the engineering worldview the universe evolves thermodynamically, a way of
152 understanding that subsumes and supersedes all possible classical scientific, mechanical worldviews.
153 Engineering is thermodynamics. Thermodynamics is engineering.

154 3. Strategy and Transition

155 In order to develop and defend the bold hypothesis there are two closely related tasks. First, we
156 need to articulate engineering thermodynamics from within an engineering conceptual framework.
157 For instance, rejecting attempts to represent Carnot’s insights in the terms of a rational mechanics.
158 Second, the proper understanding of engineering thermodynamics requires a reconsideration of the
159 *actual* history of the emergence of thermodynamics. Despite acceptance that thermodynamics
160 originally arose from engineering and was not the result of any scientific research program, many
161 historians have offered ‘rational reconstructions’ from a mechanical perspective. These begin with
162 the presupposition that the ‘real’ development must have happened a certain way, consistent with a
163 ‘rational mechanics’, because ‘we know’ that, ultimately, in the long run, the correct representation
164 of knowledge and advances in knowledge must be rational mechanical, as in the postulated scientific
165 Theory of Everything [13].

166 3.1. Donald Cardwell and the History of Thermodynamics

167 Historian of science and technology Donald Cardwell, being based at University of Manchester,
168 naturally took a special interest in the history of the industrial revolution and the crucial influence of
169 heat engines. More than other historians Cardwell realized that many of the 20th century histories of
170 science and technology misrepresented the history of thermodynamics. Cardwell came to believe that
171 the late 19th and early 20th century dominance of the mechanical worldview had led to misguided
172 ‘rational reconstructions’ of the history of science and technology [14].

173 If one accepted the dominant cultural belief that the universe is governed by one universal
174 mechanical order, ‘it stood to reason’ that advances in understanding reality must have occurred
175 ‘rationally’, mirroring the supposed ‘one’ logico-mathematically, rationally consistent mechanical
176 order governing reality. Whether advances could even potentially proceed in this way was the core
177 controversy animating the latter half of 20th century history and philosophy of science [9]. Thomas
178 Kuhn had served to crystalize a large body of diverse research suggesting the need for an alternative
179 approach to the history of science and technology. What has been lacking philosophically, over the
180 ensuing period, is a more general framework that can properly subsume and supersede the limited
181 mechanical theories and their apparently limited ways of representing both successful practice and

182 conceptual advances. Per hypothesis, we have been lacking a clear understanding of the more general
183 engineering conceptual framework [15].³

184 Cardwell came to believe that the dominant histories of thermodynamics, largely built on the
185 work of Clausius, Kelvin, Joule and Boltzmann had misrepresented both the actual history of
186 thermodynamics and, as a consequence, the correct understanding of engineering thermodynamics
187 as foundational. Cardwell reflects [16]:

188 “Almost traditionally, it seems, accounts of the development of the concepts of work and energy
189 have tended to describe them within the classical framework of Newtonian mechanics. They are seen
190 as the end products of the celebrated *vis-viva* dispute in the eighteenth century: the outcome of a
191 debate within the confines of the science of rational mechanics. I would like to suggest that this may
192 be to take too narrow a view of the case.”

193 I will argue that reconsideration of ‘the celebrated *vis-viva*’ debate reveals the origin of what
194 Atkins identified as the ‘two paths’ to thermodynamics. Cardwell’s careful scholarship on the history
195 of thermodynamics also led him to recognize the competition between the two historical approaches
196 to the formulation of thermodynamics [17]. The ‘rational mechanics’ approach, favored by theorists,
197 mathematicians and logicians, represented thermodynamics as one logically consistent axiomatic
198 system. This approach tacitly implied that advances in understanding must occur by means of some
199 logically consistent rational process. The alternative, ‘empirical mechanics’ approach, favored by
200 engineers, rejects the rationalist formulation wherein advances in understanding are ‘rationally’
201 foreseeable. In the ‘empirical mechanics’ approach advances require genuinely exploratory hands-on
202 empirical investigation resulting in novel discovery.⁴

203 Cardwell re-introduced historical consideration of the practical, ‘empirical mechanical’
204 tradition. He soon recognized this as the engineering tradition. Appropriately Cardwell discovered
205 the research and innovations of engineers such as Roger Smeaton [17] concerning the power and
206 efficiency of waterwheel designs. And he recognized these as historical antecedents of Sadi Carnot’s
207 later investigations of the power and efficiency of steam engine designs. Questions such as how to
208 design an engine for either maximum power or maximum efficiency are at the foundation of
209 engineering thermodynamics. Such fundamental engineering questions have ancient roots and yet
210 don’t even arise within the ‘just-so stories’ of the rational mechanical narrative of the history of

³ We have been lacking a philosophy of engineering and engineering worldview that could subsume and supersede the previously dominant philosophy of science and the scientific (viz. mechanical) worldview. We need to reexamine both current scientific epistemology and ontology from a new post-mechanical point of view.

⁴ What has been particularly misleading is that after each conceptually discontinuous advance the new way of understanding is re-axiomatized using the new concepts and definitions. Superficially, it can ‘appear’ that the sequence of advances have all occurred within one logico-mathematical framework, now, ‘more clearly understood’ in the concepts and definitions of this new latest axiomatization. Such an attitude is at least reasonable if one presupposes that the eventual final theory of everything will have a single, unified axiomatizable structure. Only with careful historical scholarship can it be established that the axiomatized advances are a sequence of logically discontinuous axiomatizations, each involving a paradigm shift to a more general conceptual framework that supersedes the prior axiomatized understandings. Only with quantum theory and the abandonment of the presupposition that the final theory will be mechanical, does a new approach begin to be taken seriously. Only with the embrace of post-mechanical quantum framework does the ‘rational mechanist’ dream of a conceptually uniform, logico-mathematically consistent final theory seem to be impossible.

211 thermodynamics.⁵ Cardwell's evolving hypothesis was that the real history of thermodynamics
212 requires a post-mechanical framework.

213 The emergence of the post-mechanical framework of quantum theory was completely
214 unexpected from the perspective of the rational mechanics research program. Quantum theory
215 challenged the rationalist historical narrative by undermining the claim that the classical, objectivist,
216 mechanical framework could be foundational. Quantum theory is, by its very nature, more general
217 than all possible mechanics, superseding, in particular, both Newtonian mechanics and the
218 complementary Maxwellian mechanics [18]. Following Cardwell's insight as to the need to reconsider
219 the history and foundations of thermodynamics from a post-mechanical perspective, it should not
220 perhaps have been entirely surprising to discover a fundamental link between the real origin and
221 nature of engineering thermodynamics and quantum theory.

222 Cardwell was eventually led to the work of Lazare Carnot.

223 3.2. Lazare Carnot's Engineering Worldview Project

224 Anyone who has studied the history thermodynamics is at least aware of Sadi Carnot, whose
225 *Reflexions on the Motive Power of Fire* [19], first published in 1824 but unnoticed until 1834, is often
226 cited as the founding treatise of thermodynamics. There is far less awareness in the thermodynamics
227 community of his father, Lazare Carnot, who was writing on 'engineering mechanics' (viz. per
228 hypothesis, thermodynamics) a decade or more before Sadi was born. As has recently been argued,
229 and I agree, Sadi's founding treatise on heat engines is best understood as a direct application of
230 Lazare's earlier engineering approach to understanding 'the fundamental laws of the communication
231 of movement' [20].

232 The obscurity of Lazare's important, foundational work calls for an additional comment. Very,
233 very briefly, Lazare was one of the three principals managing the French Revolution and had become
234 the General in charge of the army of the revolution. Lazare was a key influence in the decision to
235 behead Louis XVI. Subsequently, when the Bourbon monarchy was partially restored in France,
236 Lazare books were banned. It was well into the 20th century before Princeton University historian
237 Gillispie rediscovered and appreciated the significance of Lazare Carnot's fundamental contributions
238 [21]. Since then awareness of his work has been growing [20].⁶

239 Lazare's scholarship was not isolated. He was one of a number of engineers, physicists and
240 mathematicians clustered in time around the new École Polytechnique in Paris during an
241 extraordinarily productive intellectual period. Among the other faculty and students were Ampere,
242 Cauchy, Lagrange, Navier, Poinot, Fourier, Fresnel, Clapeyron and Coriolis.

243 Lazare Carnot clearly differentiates his empirical engineering mechanics project from the
244 dominant alternative rational mechanics projects. Lazare points out, definitively, that "Every person
245 knows, that in machines in movement, we always lose in time or in velocity what we gain in power
246 [22]." He continues, that after carefully examining all the rational mechanics he finds that they are
247 unable to explain this. Moreover, such options, such choices, can't even arise, can't even be made
248 sense of in any fully deterministic rational mechanics.

249 Lazare is pointing out the obvious presupposition of all engineers, that there are alternative
250 courses of action – with tradeoffs. There are options as to how a task might be accomplished, for
251 instance, to lift something directly or, more slowly by using a pulley. Lazare's 'everyone knows'
252 might more sympathetically be expressed as 'every engineer knows', although anyone active in the
253 world tacitly knows that there are typically different approaches available to accomplish any task.

⁵ Stephen Jay Gould introduced the metaphor of 'just-so stories' into the philosophy of biology as a critique of imagined explanations that 'make sense' and 'stand to reason' but lack any real empirical basis. Gould's 'just-so stories' reference is to Rudyard Kipling's 1902 *Just So Stories*, deliberately fanciful stories for children in which the stories pretend to explain animal characteristics such as the leopard's spots or the elephant's trunk.

⁶ I am currently involved in a project translating, from French into English, Lazare Carnot's two mature works of 1803: *The Fundamental Principles of Equilibrium and Motion* and, *The Geometry of Position*.

254 Prominent in Lazare's thinking is the role of simple machines identified in the ancient engineering
255 tradition.

256 Another way to characterize Lazare's project is as an attempt to develop a more general, post-
257 mechanical worldview that is able to make sense of the place the engineer, common engineering
258 knowledge and engineering practices, in the universe. The rational mechanics (viz. scientific)
259 worldviews have no way to make sense of the creative freedom presupposed in engineering.

260 3.3. Pierre Maupertuis

261 Just as Cardwell reached back in the practical engineering tradition to see the relevance of Roger
262 Smeaton to Sadi Carnot's work, it is important to seek earlier theoretical considerations contributing
263 to Lazare's seminal engineering project. The intellectual milieu in physics and mathematics in the 150
264 years prior to Lazare Carnot's (1753-1823) investigations was defined by the contributions of Galileo
265 Galilei (1564-1642), Rene Descartes (1596-1650), Isaac Newton (1642-1727) and Gottfried Leibniz
266 (1646-1716).

267 In the more immediate 50 years the work Jean d'Alembert (1717-1783), Leonard Euler (1707-
268 1783), Daniel Bernoulli (1700-1782) and Pierre Maupertuis (1698-1759) are most relevant to our
269 narrative. One foundational debate among physicists, engineers, philosophers and mathematicians
270 centered on the *vis-viva* controversy.

271 Lazare Carnot identifies Pierre Maupertuis's proposed resolution of the *vis-viva* debate as crucial
272 to his mature engineering mechanics project [22]. And it is an understanding of Maupertuis's
273 proposed resolution, I will argue, that clarifies the unexpected connection between engineering
274 thermodynamics and quantum theory.

275 The *vis-viva* debate is commonly represented as concerned with the proper understanding (viz.
276 conception) of the quantity conserved in motion and interactions. Before proceeding it is important
277 to clarify why what is conserved is a crucial foundational issue. Symmetry and conservation
278 principles are what define any mechanical framework. Therefore, the identification of just what
279 quantity is actually conserved provides the conceptual foundation of the mechanical framework.
280 Rene Descartes, in his *Mechanics* [23], had quite reasonably argued that the correct conception of the
281 quantity of motion was momentum, the product of mass times velocity (mv). For Descartes, the total
282 quantity of motion in the universe is conserved.⁷ Newton agreed, in his *Principia*, that the
283 momentum of bodies at rest or in uniform motion is conserved, in a closed (viz. isolated) system.

284 Gottfried Leibniz initiates the *vis viva* controversy, rejecting the Cartesian (viz. and implicitly
285 Newtonian) proposals. He argues that what is conserved is properly conceived of as the product of
286 mass times velocity squared (mv^2) [24][25]. However, following Cardwell's insight it is possible that
287 many of the modern accounts of the *vis viva* controversy offer us only a 'rational reconstruction' of
288 the history and supposed resolution from a mechanical perspective.

⁷ Bertrand Russell, in his *An Essay on the Foundations of Geometry*, points out that all possible geometries require a Principle of Equality (e.g. the Axiom of Free Mobility (or Congruence)). Symmetry and Conservation Principles are analogously required to define any possible rational, axiomatizable mechanics.

See also "The Meaning of Symmetry", Introduction, page 2 "First, we have the interpretation of the *equality of the parts with respect to the whole* in the sense of their *interchangeability* (equal parts can be exchanged with one another, while preserving the whole). Then, we have the introduction of specific mathematical operations, such as reflections, rotations, and translations, that are used to describe with precision how the parts are to be exchanged. As a result, we arrive at a definition of the symmetry of a geometrical figure in terms of its *invariance* when equal component parts are exchanged according to one of the specified operations." *Symmetries in Physics: Philosophical Reflections* (edited by Katherine Brading and Elena Castellani)

289 As physicist Patrick Hamill points out, although Isaac Newton and Gottfried Leibniz both
 290 invented the calculus, they had quite different conceptions of reality and how it evolved in time [26]."
 291 ⁸

292 Leibniz reasoned that every kinetic event generated a new equal and opposite potential event.
 293 To illustrate he notes that the kinetic event of raising a body to a certain height against gravity results
 294 in an equal and opposite potential kinetic event [27]. ⁹ Leibniz new dynamic equilibrium of kinetic
 295 and potential events was proposing a new more general type of 'metaphysical' framework (viz. post-
 296 mechanical), a new way of understanding reality and how it changes. The postulate that the 'quantity
 297 of motion' in the dynamic equilibrium is conserved later became the central feature of Lagrange's
 298 analytic mechanics. It is well beyond the scope of this essay to argue for a definitive resolution of the
 299 *vis-viva* debate, but Leibniz's conception of a living force (*vis viva*) appears to supersede the previous
 300 conceptions of the dead force of Cartesian and Newtonian mechanics. The 'entities' of Leibniz's
 301 reality are not inherently passive particles. In Leibniz's ontology, his entities embody the living force,
 302 like agents, and 'change' naturally on their own, by their very nature. By contrast, Newtonian entities
 303 move/change only by the action of an external agent. At least superficially, Leibniz's dynamic
 304 ontology seems to have anticipated the thermodynamic phenomenon of Brownian motion.

305 Following Cardwell's suspicion that the history and nature of thermodynamics has been
 306 misrepresented as mechanical, it seems likely, as one might have expected, that the same
 307 misrepresentation applies to the supposed resolution of the *vis viva* controversy. Indeed, Cardwell in
 308 last chapter of his book, *From Watt to Clausius*, he is quite explicit in criticizing Peter Tait's supposed
 309 resolution that dominated the English-speaking literature for 100 years [28]. As will become clear I
 310 suspect, as did Cardwell, that the *vis viva* controversy remains unresolved in the modern milieu.

311 One of the illustrative technical problems concerning motion in the *vis-viva* debates had to do
 312 with understanding of the shortest path between two points. In Cartesian mechanics the answer was
 313 simple: a straight line. But with Leibniz's tacit introduction of Newtonian gravity as a consideration
 314 there were now two components of any motion. First there was the simple linear motion with
 315 constant velocity 'v', thought of as the horizontal component. Second was the vertical component of
 316 motion governed by continuous gravitational acceleration – 'v²'. Assuming two points are neither
 317 perfectly horizontal nor perfectly vertical with respect to each other the path between the two points
 318 must be the result of some sort of combination of the two components. The empirical observation
 319 was that the actual path was quite definite and repeatable. In the ideal case this path came to be

⁸ Hamill (page 16) [26] "It is well known that Isaac Newton and Gottfried Leibniz both invented the calculus independently. It is less well known that they had different notions concerning the time development of a system of particles. Newton's second law gives us a vector relationship between the force on a particle and its acceleration. ... Leibniz believed that the motion of the particles could be better analyzed by considering their *vis viva*."

⁹ Leibniz (page 20) [27]: "Our new philosophers commonly make use of the famous rule that God always conserves the same quantity of motion in the world, In fact, this rule is extremely plausible, and, in the past, I held it as indubitable. But I have since recognized what is wrong with it. It is that Descartes and many other able mathematicians have believed that the quantity of motion, that is, the speed multiplied by the size of the moving body, coincides exactly with the moving force, or, to speak geometrically, that the forces are proportional to the product of the speeds and [sizes of] bodies." However, after considering an example of a body raised to a certain height and descending, Leibniz goes on. "Hence, there is a great difference between quantity of motion and force... Force must be calculated from the quantity of the effect it can produce, for example, by the height to which a heavy body of a certain size and kind can be raised; this is quite different from the speed that can be imparted to it. Nothing is simpler than this proof."

320 represented as the brachistochrone curve (viz. later recognized as a portion of a cycloid). The problem
 321 was how to explain this particular path, this particular combination.

322 Following his reanalysis of Fermat's earlier account of the shortest-time path of refracted light,
 323 Pierre Maupertuis argued that the brachistochrone curve, the actual, observed path, was not just any
 324 combination of the two components, but was the path optimized to take the shortest time. In fact,
 325 geometrically, by distance, it is a longer path. The continuously accelerating vertical component is
 326 what serves to differentiate the shortest time-path from the simple uniform straight line path
 327 expectation by the Cartesian and Newtonian mechanics.

328 Maupertuis's insight matured, leading to his general proposal, his Principle of Least Action: that
 329 all actual motion was an optimized combination – time-minimizing, least-effort – of these two
 330 idealized type of mechanical motion. Maupertuis's bold hypothesis was that all change and all
 331 structures and functions in the universe manifested this divine optimization [29].

332 These two idealized types of mechanical motion – one the perfectly horizontal ' mv ' and the
 333 other, the perfectly vertical ' mv^2 ' – taken individually – can only provide incomplete descriptions of
 334 actual motion. The horizontal is an idealized uniform mv -motion where the vertical component is
 335 zero. The vertical is an idealized continuously accelerating mv^2 -motion where the horizontal
 336 component is zero. Since they are orthogonal the one way of describing motion cannot be reduced
 337 to, cannot be expressed in terms of, the other. They are contraries. In modern parlance, they are
 338 conjugates. They are logico-mathematically and conceptually incommensurable, per hypothesis,
 339 complementary [30].

340 In so far as mechanical frameworks are defined by their symmetry and conservation
 341 presuppositions, each of these opposite types of motion defines a different type of mechanical
 342 framework. Each framework with its corresponding principles of conservation and symmetry.
 343 Maupertuis's great insight is that both perspectives must be valid, depending on the choice of frame
 344 of reference. Maupertuis is pleased that the greatest mathematician of the era, Leonard Euler,
 345 comments approvingly of his insight. Specifically, Euler points out that it applies to, and helps us to
 346 understand, the orbits of the planets as optimized combinations of their linear and curvilinear
 347 components.¹⁰

348 Maupertuis eventually takes us one step further to denying that perfectly horizontal (mv)
 349 mechanical motion and perfectly vertical (mv^2) mechanical motion are realizable. Consequently, no
 350 actual motion can be completely described or explained mechanically – that is, in terms of *one*
 351 idealized mechanics (viz. consistent with the symmetry and conservation presuppositions of one type
 352 of mechanics). Furthermore, since the actual paths are a combination of orthogonal, conjugate
 353 components, the paths cannot be characterized as any sort of simple sum of the two incommensurable
 354 types.¹¹

355 Maupertuis needs a new way to portray the actual optimized path between any two points. Here
 356 he brilliantly introduces the notion of 'action'. All possible paths are possible actions and the actual
 357 paths, the actual actions, are the optimized paths of least action. What is important to recognize here
 358 is that, with the introduction of the notion of action, Maupertuis is introducing a conceptually novel
 359 framework – the action framework.

360 Maupertuis's action framework subsumes and supersedes all possible mv -mechanical
 361 frameworks and all possible mv^2 -mechanical frameworks. By subsuming, Maupertuis's action
 362 framework is able to explain the limited, incomplete successes of each opposite, idealized mechanics.

¹⁰ The stable and regular planetary orbits also serve to illustrate Maupertuis's emerging post-mechanical worldview. The stabilities and regularities (viz. the mechanical-like relations) of reality are to be understood in a new way in Maupertuis action framework. These specific optimizations are like 'creative design solutions'. Optimization is unique to engineering where problem solving is value actualization. From an engineering point of view Maupertuis's optimized actions are the result of engineering work.

¹¹ More generally the paths cannot be related by any continuous, logico-mathematical function.

363 Maupertuis's action framework is post-mechanical, conceptually superseding, understanding all
364 mechanical concepts and frameworks in a new way, as partial, limited idealizations of actual
365 phenomena. The action framework understands the idealized mechanical conceptions of motion in a
366 new way – the new way being is in terms of action.

367 That these opposite idealized mechanical types are actually incommensurable is suggestively
368 supported by the historical independence within Newtonian mechanics itself of the Three Laws (viz.
369 where motion is always linear) and the Law of Gravitation (viz. accounting for the curvilinear
370 component of actual motions). Newton's Three Law might be reasonably represented as a sort of
371 generalization of the Cartesian mechanics since all motion in both cases is presumed to be naturally
372 rectilinear. Newton's Theory of Gravity however stands apart in so far as it entails an accelerating
373 curvilinear component that is not reducible to uniform rectilinear motion.¹²

374 3.4. Engineering Thermodynamics and Quantum Theory

375 In the context of my overall bold hypothesis there seems to be a foundational link, generally
376 unexpected, between engineering thermodynamics and quantum theory.

377 In the several decades before quantum theory one might have characterized our uncomfortable
378 situation as having an embarrassing over-abundance of different types of 'objectivities', for instance,
379 the Newtonian and the Maxwellian. With quantum theory we have something more like a range of
380 potential objectivities – each practically optimized combination, valid within its defining constraints.
381 Maupertuis's thesis that there is an irreducible component of each opposite type of idealized
382 mechanics in all change is entirely analogous to Louis de Broglie's quantum theory thesis that every
383 observation involves an irreducible component of the complementary particle and wave aspects of
384 reality.¹³

385 With even superficial reflection there are other connections, at least analogies, between Lazare
386 Carnot's engineering thermodynamics project and quantum theory. Both require an active agent, an
387 actualizing observer or a participant engineer, as an essential, irreducible component of any self-
388 referentially coherent representation. This participant aspect of quantum theory has been thoroughly
389 enigmatic in the attempts at a mechanical representation of quantum theory. Per hypothesis, in a
390 more general, superseding engineering worldview 'the observer of quantum theory' is understood
391 in a new way, as a naturally active, inquiring, actualizing engineer.

392 In both quantum theory and engineering thermodynamics prior to the choice of the appropriate
393 frame of reference, boundary conditions and experimental setup the future is indeterminate. The
394 present, although constraining, does not determine a unique future. The observer's choice in
395 quantum theory that collapses the wave function is usually characterized as 'analytically arbitrary'.
396 The 'indeterminate situation' in engineering thermodynamics, by analogy at least, might be
397 represented in terms of the Gibbs free-energy situation – constrained but enabling. However, it is
398 important to recognize, per hypothesis, that the Helmholtz free-energy situation is complementary.
399 The Gibbs and Helmholtz situations define the possibility of performing two alternative, opposite
400 types of work.

401 It is perhaps helpful to recall that quantum theory was, and still is, a theory of thermodynamics.
402 Max Planck's investigation of black body radiation is properly understood as an engineering

¹² Of all the possible combinations what selects what is optimum? Maupertuis suggests that the order of the universe, the structures and functions and, how they evolve, reflect design solutions and, consequently, some sort of purpose (teleos) – practical and perhaps divine.

¹³ Bohr's insight was that not only are idealized particle and wave phenomena complementarity, but the idealized structure and function of the experimental designs required to observe them must be complementary. Indeed, the sequence of actions required to generate those mechanically idealized experimental designs must be complementary.

403 thermodynamics research project. Per hypothesis, the proper history of quantum theory requires an
404 engineering thermodynamics framework.

405 3.4.1. A Little Confusion

406 Euler's endorsement certainly emboldened Maupertuis. Then something strange and truly
407 confusing happened. Euler says in effect: 'Yes, Maupertuis's fundamental insight about the
408 optimized structures and functions of reality is correct', but it's not very 'useful' [29]. Here is where
409 the two historical paths identified by Atkins acquire their more modern characteristics. If I
410 understand Euler, he is saying that Maupertuis's insight isn't very useful for empirical mechanical
411 inquiry and practical problem solving.

412 What emerges is the Euler-Lagrange line of development defining a new type of mechanics –
413 Lagrangian. What differentiates Lazare's engineering thermodynamics from the new Euler-Lagrange
414 advance is that the latter adopts symmetry and conservation principles that keep it well within the
415 foundational tradition of determinate mechanics. Despite the introduction of the new types of
416 dynamic equilibrium between kinetic and potential, Lagrangian mechanics is still mechanically
417 symmetric and, ontologically, 'energy' is conserved.

418 However, as Coopersmith [31] notes Lagrangian mechanics falters in its ability to account for
419 dissipation. Per hypothesis, this 'dissipation' is the conjugate mechanical component.¹⁴ In
420 Lagrangian mechanics what is conserved, the energy, is of *one type*. In the Lagrangian system each
421 present defines a unique determinate 'objective' future in the classical scientific sense. And yet there
422 are no actualizing observers and, no constructive engineering agents.

423 The confusion, according to this analysis, generated by the Euler-Lagrange path is compounded
424 by their introduction of idealizing mechanical definitions of both 'action' and the Principle of Least
425 Action.

426 Historically, despite theoretical limitations, as Euler envisioned, Lagrangian mechanics has been
427 tremendously useful. This led to further advances in the work of William Rowan Hamilton, plausibly
428 still within the mechanics research program. However, whether 'energy' is conserved has been
429 questioned and, the nature of the defining symmetry is arguably somewhat ambiguous. Nonetheless
430 the Hamiltonian toolkit has proved quite useful in experimental investigations and applications of
431 quantum theory.

432 Lazare Carnot actually provides the clearest, most accessible account of what is behind Euler's
433 not very 'useful' critique of Maupertuis's insight. In one of Lazare's earliest contributions, later
434 published as *Reflexions On the Metaphysical Principles of the Infinitesimal Analysis*, notes that the use of
435 infinitesimal analysis lacks formal rational justification [32]. Basically, it doesn't make sense. To see
436 his point, one need only reflect on the inherently ambiguous or, perhaps outright self-contradictory,
437 statements common in modern thermodynamics such as – 'the piston moves infinitely slowly'.
438 Lazare argues that infinitesimal analysis, nonetheless, is an essential tool in empirical mechanics
439 research. If reality involves complementary orders, then to empirically discover the 'useful'
440 relationships of one idealized mechanical order you need to minimize the complementary aspect,
441 making it practically irrelevant, 'ignorable'. In suggesting a superseding understanding of
442 infinitesimal analysis, Lazare is suggesting a superseding engineering understanding of the use and
443 value of idealizations in empirical inquiry.

444 In Lazare's superseding understanding 'objectivity' is 'real' but always bounded. Engineering
445 'objectivity' is never the universal time-space invariant objectivity imagined in the classical scientific

¹⁴ Coopersmith (page 36) [31]: "It is very strange to say, but this profound yet banal human experience of time plays no part whatsoever in the dynamics of either Newton or Lagrange. Even though the dynamics examines macroscopic effects (but, crucially, microscopic dissipative effects, like friction or air resistance, are ignored) there is no sense of time flowing, no difference between making time run forward or backward in the equations. As Einstein wrote: "... the distinction between past, present, and future is only an illusion, however persistent."

446 tradition. From within a more general engineering worldview Lazare presents a justification of
447 differential calculus as not only 'useful', but as an essential tool in empirical research. Inquiry is newly
448 understood as seeking to discover the regularities and uniformities describable by idealizing
449 continuous functions within 'objective' boundary conditions. At the same time, Lazare is offering a
450 more general, non-standard logic justification of induction – within uniform boundaries [33]. In
451 standard, formal logic, induction is not deductively valid, but within the boundaries of a stable
452 uniformity, within an engineering 'objectivity', it is valid. In the modern post-mechanical context,
453 Newtonian mechanics and Maxwellian mechanics are both 'objectively valid' in the engineering
454 sense, within boundary condition and with respect to specific types of experimental setups.

455 Lazare's representation of 'science' is similar to Henri Poincare's conventionalist model wherein
456 scientific inquiry, by its very nature, must always be idealizing [33]. In the modern debate about the
457 falsifiability of scientific theories, University of London philosopher of science Imre Lakatos argued
458 in keeping with Lazare's understanding that all meaningful scientific theories are necessarily false –
459 in the sense of being inherently incomplete (viz. bounded). No meaningful, falsifiable theory (viz.
460 knowledge) can achieve the classical objectivist ideal of being demonstrably reproducible over
461 changes in time and location, of being universally time-space invariant. Lakatos attributes a similar
462 position to George Hegel who suggested that 'to conceive is to falsify' in that it requires selecting a
463 way to conceive, to observe, to understand [34]. One way to express this is to say that reality is more
464 ample than any single conception, than any single way of observing. In Lazare's engineering
465 worldview reality is more ample than any single mechanical description.

466 Bohr emphasized that to observe and investigate the particle-like aspect of reality you need a
467 different type of experimental setup than if you wish to investigate the wave-like aspect of reality.
468 When Bohr's colleagues pressed him as to the nature of underlying quantum reality, he responded:
469 'There is no quantum reality. Get over it.' Bohr was emphasizing that quantum theory is post-
470 objective as well as post-mechanical, subsuming and superseding the idealized particle and wave
471 ontologies of the corresponding mechanics. Consequently, there are no particles and there are no
472 waves in the Newtonian or Maxwellian senses. Physicist Nick Herbert offers what remains as one of
473 the best presentations of the problem of making sense of quantum reality [35].

474 Einstein expressed the problem of replacing the classical ideal of 'physical reality' with a more
475 general, more advanced quantum reality (page 81) [36]:

476 "[Classically] Physics is an attempt conceptually to grasp reality as it is thought independently
477 of its being observed. In this sense one speaks of "physical reality." In pre-quantum physics there
478 was no doubt as to how this was to be understood. In Newton's theory reality was determined by a
479 material point in space and time; in Maxwell's theory, by the field in space and time. In quantum
480 mechanics it is not so easily seen."

481 Einstein's critique had pointed out that Newton's physics tacitly presupposed absolute
482 simultaneity, entailing that everything happens at the same time. However, this is only possible if
483 everything happens in the same place, thus – Newtonian reality is a 'material point in space and
484 time'. In Maxwell's physics reality is the idealized field completely distributed in space and time.
485 Newtonian reality is ideally completely local and Maxwellian reality is ideally completely non-local.
486 I have argued previously that the Newtonian space-time framework and the Maxwellian space-time
487 framework are complementary. If correct, then Einstein's preference for the Maxwellian space-time
488 framework in Relativity reflects a 'useful' bias to a mechanical framework, away from the more
489 general indeterminate action framework [7]. Per hypothesis, both quantum theory and relativity
490 share the same foundation and they are more completely understood as one theory from an
491 engineering thermodynamics point of view.

492 Wolfgang Pauli begins to articulate the characteristics of the new more general, post-mechanical
493 framework of quantum theory (page 36) [37]:

494 "The relation of indeterminacy, which is inherent in the laws of nature, just makes mutually
495 exclusive the experiments which serve to check the wave properties of an atomic object, and the other
496 experiments which serve to check its particle properties. The significance of this development is to
497 give us insight into the logical possibility of a new and wider pattern of thought. This takes into

498 account the observer, including the apparatus used by him, differently from the way it was done in
499 classical physics, both in Newtonian mechanics and in Maxwell-Einstein field theories.

500 "In the new pattern of thought we do not assume any longer the *detached observer*, occurring in
501 the idealizations of this classical type of theory, but an observer who by his indeterminable effects
502 creates a new situation, theoretically described as a new state of the observed system. In this way
503 every observation is a singling out of a particular factual result, here and now, from the theoretical
504 possibilities, therefore making obvious the discontinuous aspect of physical phenomena."

505 In the early days of quantum theory Pauli worked out the mathematics of Werner Heisenberg's
506 initial insightful theory. In presenting the results to Heisenberg, Pauli comments: 'You can investigate
507 in the p-way or you can investigate in the q-way, but if you try to do both at the same time it will
508 drive you crazy [37].'

509 Quantum pioneer Louis de Broglie made the point that in the quantum worldview, in all
510 idealizing particle experiments there is an irreducible wave aspect and in all idealizing wave
511 experiments there is a quantized particle aspect [38]. In Newton's original particle mechanics there
512 are no waves and in Maxwell's original wave mechanics there are no particles (viz. no discontinuities
513 or localizations). Quantum theory is post-mechanical subsuming and superseding all possible
514 mechanics in conjugate, complementary pairs.¹⁵

515 3.5. Quantum Theory as Engineering Thermodynamics

516 In the early 20th century, from a mechanical point of view, something completely unexpected
517 and enigmatic happened. Quantum theory gradually emerged and matured. Central to my bold
518 hypothesis is that what connects the engineering origin of thermodynamics with quantum theory is
519 the concept of action. Maupertuis's original indeterminate, dualistic notion of action, that was
520 mechanically idealized in Lagrange's analytic mechanics, reappears in Max Planck's quantum of
521 action.

522 Many modern portrayals of quantum theory emphasize the ontological enigma of particles and
523 waves associated with the two-slit experiment. These depictions have unintentionally served to
524 deemphasize that quantum theory is a theory concerned with thermodynamic phenomena. Planck's
525 research into black body radiation was thermodynamic research both practically and theoretically.
526 His research was funded by the new German electric light industry seeking the optimum relationship
527 between power input and light output. Planck himself was hoping to overturn Boltzmann's
528 introduction of statistical mechanical concepts into thermodynamics (viz. into physics) [39].

529 Schrodinger's popular wave function is clearly an 'energy' formula. Schrodinger had originally
530 imagined his approach to quantum theory was a return to 'sensible' wave mechanics [40]. In both
531 Maupertuis's and Planck's action frameworks, prior to making a choice of the appropriate boundary
532 conditions, and how to engage (viz. the choice of experimental setup), the situation facing the
533 observer/agent is indeterminate. Max Born made clear that the 'situations' characterized by
534 Schrodinger's approach were initially indeterminate, prior to the observer's choices [41]. In Lazare's
535 framework the constrained indeterminacy defines the engineer's 'problematic' situation, the
536 constrained range of opportunities to perform work to solve a problem and actualize value [42].

537 3.6. Atkins's Dissymmetry Thesis and Maupertuis's Evolution

¹⁵ Of course, in the intellectual milieu of Maupertuis and the Carnots, there was no electromagnetic theory. However, in fact, conjugates are ubiquitous throughout physics and per hypothesis, in all the sciences and mathematics. From ancient times the question of a geometric relation between lines and curves was of central concern (viz. squaring the circle). Newton's famous thought experiment, 'Newton's Bucket', highlighted his concern with the relation between linear and curvilinear motions. See also Euler on lines and curves. I think it is somewhat embarrassing that even in today's mechanics, rotation is accounted for in terms of 'fictional forces'.

538 Peter Atkins dissymmetry thesis is relevant to the question of the proper foundations of
539 thermodynamics [1]. Atkins argues that the historical discovery of the dissymmetric character of
540 thermodynamic phenomena meant that thermodynamics phenomena could never be reduced to
541 mechanical phenomena as defined within symmetric mechanical frameworks. Atkins suggests that
542 the discovery of thermodynamics phenomena constitutes the discovery of an essential, irreducible
543 dissymmetric aspect of the nature reality. If true I take it to be supportive of my bold hypothesis. Per
544 hypothesis, if the dissymmetric characteristic of phenomena is more fundamental than the idealized
545 symmetric characteristics, it means that we need a more general, subsuming, superseding, post-
546 mechanical framework to understand the actual thermodynamic character of reality. In such a
547 broader view, the success of any possible mechanics would be understood as a limited special case
548 within the more general, foundational dissymmetric engineering thermodynamic worldview.
549 Similarly, since the more general indeterminate 'action' of quantum theory cannot be reduced to the
550 concepts of classical particle mechanics and/or wave mechanics, a more general post-mechanical
551 framework is required to understand the dissymmetric quantum worldview.

552 There is another important entailment of the dissymmetry thesis. Classically symmetric systems
553 are always conservative – zero-sum games. In a simple Newtonian system every action has an equal
554 and opposite reaction. If the action and the reaction are of *the same type*, then the net change is zero.
555 In closed, isolated mechanical systems with one type of ontology, one uniform type of 'energy', the
556 net change of the ontological quantity must be zero. Cambridge physicist John Barrow, in his *The*
557 *Book of Nothing*, develops the implication of a scientific worldview defined by symmetry and
558 conservation principles (viz. where the universe is a closed, isolated mechanical system) [43]. Barrow
559 argues that if you add up all the charge in such a universe it perfectly balances and cancels, so there
560 is no net charge. Similarly, if you add up all the motion (as in $E = mv^2$) it must also balance and add
561 up to zero. The curious implication is that the sum of any symmetric, conservative mechanical
562 universe –is zero, the reality is nothing.¹⁶

563 Maupertuis had certainly noticed that since the components of all action, of all change are
564 opposites (viz. per hypothesis, complementary), they are *not of the same type*. As a Consequence,
565 neither the result of any action nor the sum of the actions of a system over time can be net zero. Even
566 though the opposite components form a new type of dynamic equilibrium, it is not 'net zero'
567 symmetric in the classical sense. Therefore, all systems must have an irreducible aspect of net change.
568 They must develop. Because they are different types, the optimizing action-reaction processes in
569 Maupertuis's worldview produce a net, non-zero change. Per hypothesis, since the net change is post-
570 mechanical (viz. can't be understood in terms of only one type of mechanics) the change is, plausibly,
571 properly represented as having an irreducible an emergent, quality. In the action framework
572 processes are necessarily generative of a net historical product. What is the product? Per hypothesis,
573 the net product over time is a cumulatively actualizing, historically evolving non-zero-sum universe.
574 It is not coincidental that subsequent to his insights leading to the Principle of Least Action,
575 Maupertuis composed two major works on evolution [44][45]. If the engineering thermodynamic

¹⁶ Atkins (page 9) [1]: "In 1851 Kelvin adopted that, after all, physics was the science of energy. Although forces could come and go, energy was here to stay. This concept appealed deeply to Kelvin's religious inclinations: God, he could now argue, endowed the world at the creation with a store of energy, and that divine gift would persist for eternity, while the ephemeral forces danced to the music of time and spun the transitory phenomena of the world.*"

"*A mischievous cosmologist might now turn this argument on its head. One version of the Big Bang, *the inflationary scenario*, can be interpreted as meaning that the total energy of the Universe is indeed constant, but constant at zero! The positive energy of the Universe (largely represented by the energy equivalent of the mass of the particles present, that is, by the relation $E = mc^2$) might exactly balance the negative energy (the gravitational attractive potential energy), so that overall the total might be zero. Thus, Kelvin's God may have left a nugatory legacy."

576 framework turns out to the more general, post-mechanical foundation for understanding reality, it
577 seems plausible that Maupertuis's contribution to the theory of biological evolution will subsume
578 and supersede the mechanistically-based Darwinian, and neo-Darwinian approaches.

579 All this is completely consistent with various post-mechanical, participant representations of
580 quantum theory, for instance, by Princeton's John Archibald Wheeler [46], Berkeley's Henry Stapp
581 [47] and Harvard's Alfred North Whitehead [48].

582 The hypothesis that the evolution of the universe is a qualitative, cumulatively emergent,
583 recursively enabling engineering enterprise requiring an experimental research and development,
584 requiring a concomitant evolving engineering intelligence is certainly not new. It is the theme of
585 Plato's dialogue, *Timaeus* [49], where the question being explored is: How did the universe come to
586 be as it is? The answer suggested by *Timaeus* is that the evolution is an engineering enterprise of an
587 architekton (viz. master craftsman (engineer) and/or a demiurge (the public worker) [50]. *Timaeus*
588 assures us that the 'plan' is never analytically, deterministically pre-specifiable. Yet the recursively
589 enabling path of development is constrained, always seeking a more desirable future

590 3.7. Reflection on Current Thinking

591 Physicist Jim Baggott, in his excellent review of the current situation in his book, *Farewell to*
592 *Reality: How Modern Physics Has Betrayed the Search for Scientific Truth*, emphasizes that the questions
593 of quantum realism remain unresolved [51].

594 Despite expressions of serious misgivings current prominent physicists continue to move to the
595 default mechanical framework (viz. defined by symmetry and conservation principles) in their
596 representations of thermodynamics. Columbia University physicist Brian Greene, in his book, *The*
597 *Fabric of the Cosmos*, relates his experience on learning of Loschmidt's critique of Boltzmann's
598 mechanical representation of thermodynamics (page 168) [4]:

599 "When I first encountered this idea many years ago, it was a bit of a shock. Up until that point,
600 I had thought I understood the concept of entropy fairly well, but the fact of the matter was that,
601 following the approach of textbooks I'd studied, I'd only ever considered entropy's implications for
602 the future. And, as we've just seen, while entropy applied toward the future confirms our intuition
603 and experience, entropy applied toward the past just as thoroughly contradicts them. It wasn't quite
604 as bad as suddenly learning that you've been betrayed by a longtime friend, but for me, it was pretty
605 close."

606 String Theory was initially conceived as a more enlightened physics based firmly in taking
607 thermodynamics as foundational [52]. String Theory's all-important beta-function comes directly
608 from thermodynamics. Yet Greene, endorsing String Theory, assured me [Personal Communication]
609 that it is fully deterministic, keeping it within the mechanical paradigm.

610 Cal Tech physicist Sean Carroll, in his book, *From Eternity to Here* offers a number of penetrating
611 critiques of the standard mechanical Boltzmannian representation of thermodynamics. In his course
612 *The Mysteries of Physics: Time*, Carroll offers (page 220) [53]:

613 "What Boltzmann had bequeathed was a set of machinery that didn't have an arrow of time
614 built in. It could explain entropy going up toward the future, but it also explains entropy going up
615 toward the past, which nobody thought was true. The challenge was could you use these time-
616 symmetric underlying laws of physics to derive a time asymmetric conclusion. The answer is no.
617 Loschmidt was right. It was not that he was making some mistake or that Boltzmann wasn't careful
618 enough. Loschmidt's reversibility objection is absolutely valid.

619 "If all you have to work with are underlying laws of physics that are symmetric with respect to
620 past and future, you do not derive a different behavior for the future than you do for the past. You
621 need to add something to that machinery, you need to add an extra assumption, and you need to add
622 an extra assumption that is explicitly asymmetric with respect to past and future. That extra
623 assumption is what we call the past hypothesis."

624 Columbia University philosopher of physics, David Albert, has offered still the best presentation
625 of the past hypothesis [54]. Although the introduction of an essential asymmetry (viz. dissymmetry)
626 would seem to entail the need for a post-mechanical framework, in his latest contribution Carroll

627 reassures us that the 'real', hidden, underlying reality has no participants, is completely symmetric
628 and 'energy' is conserved [55].

629 Perimeter Institute physicist Lee Smolin in his 2006 book, *The Trouble with Physics: The Rise of*
630 *String Theory, The Fall of Science, and What Comes Next* [56], expressed the growing dissatisfaction with
631 the state of physics of many within the physics community. However, in his recent attempt to explore
632 'what's next', *Time Reborn: From the Crisis in Physics to the Future of the Universe*, he has been unable to
633 find a way out of the tradition of the mechanical paradigm [57]. Smolin offered the following personal
634 reflection to an incoming class of physics graduate students [58]:

635 "When my generation entered physics in the 1960s and 1970s, we were enthusiastic and quite
636 hopeful about our prospects of resolving the questions of quantum reality. The founders of quantum
637 physics and the subsequent generation had simply given up. -- It's now 2010, and it has become
638 rather Kafkaesque that we have made no progress whatsoever."

639 Philosopher of physics Craig Callender, at UC San Diego, originally one of best and most
640 prominent critics of the mechanical interpretations of thermodynamics has most recently taken a turn
641 to the dark side (viz. deterministic mechanics) explicitly abandoning any role for participant agency
642 [5].

643 On a more hopeful note, leading Los Alamos particle physicist, Geoffrey West having morphed
644 to become the President of the Santa Fe Institute, the leading edge think tank founded by Nobel
645 Laureate physicist Murray Gell-Mann, expresses what I take to be a more enlighten view [59]:

646 "All the laws of physics can be derived from the principle of least action which, roughly
647 speaking, states that, of all the possible configurations that a system can have or that it can follow as
648 it evolves in time, the one that is physically realized is the one that minimizes its action. Consequently,
649 the dynamics, structure, and time evolution of the universe since the Big Bang, everything from black
650 holes and the satellites transmitting your cell phone messages to the cell phones and messages
651 themselves, all electrons, photons, Higgs particles, and pretty much everything else that is physical,
652 are determined from such an optimization principle.

653 "Optimization principles lie at the very heart of all of the fundamental laws of nature, whether
654 Newton's laws, Maxwell's electromagnetic theory, quantum mechanics, Einstein's theory of
655 relativity, or the grand unified theories of the elementary particles. Their modern formulation is a
656 general mathematical framework in which a quantity called the action, which is loosely related to
657 energy, is minimized." ¹⁷

658 4. Discussion and Conclusions

659 Following the hints from Peter Atkins that there were two distinct historical paths in the
660 development of modern thermodynamics, and that both approaches and corresponding formulations
661 are still alive and well, I considered the relation between them. Atkins postulated that they are
662 complementary. I offered a bold hypothesis that engineering thermodynamics (viz. properly
663 understood) is more general than any mechanical formulation of thermodynamics.

664 I argued that engineering thermodynamics is post-mechanical and formally subsumes and
665 supersedes all possible mechanical formulations of thermodynamics. The limited successes of the
666 mechanical formulations are to be explained as based on idealizations and understood in a new way,
667 more generally, in the context of optimizing engineering action. I concluded that engineering
668 thermodynamics is the true foundation of thermodynamics.

669 Accordingly, the true history of thermodynamics is the history of engineering thermodynamics.
670 I argued in support of Donald Cardwell contention that most modern historians misrepresent the
671 history of thermodynamics. Because they reason from mechanical presuppositions they generate

¹⁷ In mechanical frameworks the ontology (viz. 'energy') is of only *one uniform homogeneous type*. There is no need to optimize – just calculate the unique determinate future from the present. Per hypothesis, optimization of qualitatively distinct conjugate (viz. complementary) components is characteristic of both post-mechanical engineering thermodynamics and quantum theory understandings of reality.

672 misguided 'rational reconstructions' of the history of thermodynamics. Cardwell's proposed research
673 program is to reconsider both the history and proper understanding of thermodynamics from a post-
674 mechanical perspective. I reaffirmed his thesis that thermodynamics should be understood as part of
675 the engineering tradition that reaches back to ancient times.

676 I argued that engineer Lazare Carnot, the father of Sadi Carnot, is a crucial contributor in the
677 history of engineering thermodynamics. Lazare Carnot differentiates his engineering research
678 program by emphasizing the inadequacy of any rational mechanical worldview to account for what
679 'everybody knows' – that we always lose in time or in velocity what we gain in power. Lazare sought
680 a more general, empirical engineering framework that would provide a coherent understanding of
681 the place of engineers and engineering in reality. His engineering framework is overtly post-
682 mechanical, intended to subsume and supersede all possible rational mechanical frameworks.

683 Per hypothesis, Lazare's engineering mechanics is, literally, engineering thermodynamics. The
684 history and foundations of thermodynamics makes sense only from within a self-referentially
685 coherent engineering understanding of reality.

686 Lazare identifies Pierre Maupertuis's resolution of the *vis-viva* debate and his post-mechanical
687 Principle of Least Action as a key intellectual antecedent. Although Maupertuis formulation was
688 'somewhat vague' Lazare realized that he had proposed a post-mechanical theory of change. In
689 Maupertuis's new action framework, the present is both constrained and enabled and does not
690 uniquely determine the future. The present is indeterminate and the future emerges through the
691 optimizing choices of the embedded agency (viz. quantum observers or constructive engineers). In
692 quantum theory and Lazare Carnot's engineering framework it is the choices, always involving
693 uncertainty, that actualize the future. Since the choices could have been different, within the
694 constrained range of possible actions, it must be that the narrative history might have evolved
695 differently.

696 Unexpectedly, Maupertuis's inclusive resolution of the complementary mechanical frameworks
697 involved in the *vis-viva* debate, followed by Lazare's clarifications, suggested a link to modern
698 quantum theory. In keeping with Cardwell's initial suspicion, I argued that the deep link could be
699 understood in terms of their common concept of 'action'. Dominated historically by the fully
700 determinate, mechanical idealization of action in Lagrangian mechanics, Maupertuis's original
701 dualistic, indeterminate conception finally re-emerges in Planck's quantum of action. Since quantum
702 theory arose from Planck's thermodynamic research and both quantum theory and engineering
703 thermodynamics require an embodied agent to actualize an otherwise indeterminate future I
704 reasoned, per hypothesis, that they share, in some fundamental, foundational sense, the same post-
705 mechanical framework.

706 I argued that Atkin's thesis, that the discovery of thermodynamic phenomena constituted the
707 discovery of an irreducible, post-mechanical dissymmetric aspect to reality, is further support for the
708 bold hypothesis. The classical mechanical principles of symmetry and conservation are valid but
709 limited special cases to be understood in a new way within the more general, foundational
710 dissymmetric engineering thermodynamic worldview. I argued that the action-reaction dissymmetry
711 of complementary types of action entails that reality is not historically zero-sum in the mechanical
712 sense. The engineering thermodynamic worldview must have a naturally generative aspect resulting
713 in an irreducible cumulative, historical, qualitatively emergent aspect of reality.

714 References

- 715 1. Atkins, P. W. (1984) *The 2nd Law: Energy, Chaos and Form* (p7-9). Scientific American Library, W.H. Freeman.
716 New York. ISBN 0-7167-6006-1
- 717 2. Atkins, Peter. (2007) *Four Laws That Drive the Universe*. Oxford University Press. Oxford. ISBN 978-0-19-
718 923236-9

- 719 3. Carroll, Sean. (2010) *From Eternity to Here: The Quest for the Ultimate Theory of Time*. Dutton. Boston ISBN
720 978-0-525-95133-9
- 721 4. Greene, Brian. (2007) *The Fabric of the Cosmos: Space, Time and the Texture of Reality*. Random House,
722 New York ISBN 0375727205
- 723 5. Callender, Craig. (2017) *What Makes Time Special?* Oxford University Press. Oxford ISBN 978-0198797302
- 724 6. Popper, Karl. (2002) *Conjectures and Refutations: The Growth of Scientific Knowledge*. Routledge Classics.
725 London ISBN 978-0415285933
- 726 7. Bristol, Terry. (2016) *Give Space My Love: An Intellectual Odyssey with Dr. Stephen Hawking*. Institute for
727 Science, Engineering and Public Policy, Portland Oregon ISBN 978-0940530010
- 728 [8.](#) Bohr, Niels. (1976), Rosenfeld, L.; Nielsen, J. Rud, eds., *Niels Bohr, Collected Works, Volume 3, The*
729 *Correspondence Principle (1918–1923)*, 3, Amsterdam: North-Holland ISBN 978-0444532879
- 730 9. Kuhn, Thomas S. (1962) *The Structure of Scientific Revolutions*. University of Chicago Press. Chicago IL
- 731 10. Vincenti, Walter. (1990) *What Engineers Know and How They Know It*. John Hopkins University Press.
732 Baltimore Maryland ISBN 978-0801839740
- 733 11. Bristol, Terry. "The Engineering Knowledge Research program" in Fritzsche, Albrecht and Sascha Julian
734 Oks (Eds). (2018) *The Future of Engineering: Philosophical Foundations, Ethical Problems and Application*
735 *Cases*, Springer. Heidelberg, Berlin, New York ISBN 978-3319910284
- 736 12. Petroski, Henry. (2010) *The Essential Engineer: Why Science Will Not Solve Our Global Problems*. Knopf
737 Doubleday. New York ISBN 978-0307272454
- 738 13. Barrow, John. (2007) *New Theories of Everything (Gifford Lectures)*. Oxford University Press, USA ISBN
739 978-0192807212
- 740 14. Cardwell, D.S.L. (1989) *From Watt to Clausius: The Rise of Thermodynamics in the Early Industrial Age*.
741 Iowa State University Press, Iowa City, Iowa ISBN 978-0801406782
- 742 15. Bristol, Terry. "The Philosophy of Engineering and the Engineering Worldview" page 103ff, in Mitcham,
743 Carl et al. (eds) (2018) *Philosophy of Engineering: East and West*, Springer, Heidelberg, Berlin, New York
744 ISBN 978-3319624488
- 745 16. Cardwell, D.S.L. (1967) "Some Factors in the Early Development of the Concepts of Power, Work and
746 Energy", *The British Journal for the History of Science*, Vol. 3, No. 3 (Jun., 1967), pp. 209-224
- 747 17. Kuhn, Thomas S., "Mathematical versus Experimental Traditions in the Development of Physical Science."
748 in: *The Journal of Interdisciplinary History* 1976 (7),1-31. Reprinted in Kuhn, Thomas. (1977) *The Essential*
749 *Tension*, 31-65. University of Chicago Press, Chicago Illinois ISBN 978-0226458052
- 750 18. Gamow, George. (1985) *Thirty Years that Shock Physics: The Story of Quantum Theory*. Dover
751 Publications, Mineola, New York ISBN 978-0486248950

- 752 19. Carnot, Sadi (author) and Robert Fox (editor ad translator) (1985) *Reflexions on the Motive Power of Fire: A*
753 *Critical Edition with the Surviving Scientific Manuscripts*, Manchester University Press, Manchester, England
754 ISBN 978-0936508160
- 755 20. Gillispie, Charles C. and Raffaele Pisano. (2014) *Lazare and Sadi Carnot: A Scientific and Filial*
756 *Relationship*. Springer, Heidelberg, Berlin, New York ISBN 978-9401780100
- 757 21. Gillispie, Charles. (1971) *Lazare Carnot*, Savant. Princeton University Press, Princeton New Jersey ISBN
758 978-0691080826
- 759 22. Carnot, Lazare. (1808) *On Machines in General*, p.10 (*Essai sur les machines en général (I part)*), in:
760 *Philosophical Magazine: comprehending the various branches of science, the liberal and fine arts, agriculture,*
761 *manufactures, and commerce*. Tilloch A (ed). Vol XXX. Murray J, London, pp 8–14; pp 154–158; pp 208–221; pp
762 310–320.
- 763 23. Rene Descartes, *Principia philosophiae*, in *Oeuvres de Descartes*, ed. Charles Adam and Paul Tannery, 13
764 vols. (Paris: Cerf, 1897-1913), Vol. VIII, p. 61.
- 765 24. Smith, George E. (2006) "The *vis viva* dispute: A controversy at the dawn of dynamics", *Physics Today* 59, 10,
766 31, American Institute of Physics, College Park, Maryland
- 767 25. Iltis, Carolyn. (1971) "Leibniz and the *Viz Viva* Controversy", *ISIS*, Vol. 26, No. 1, University of Chicago
768 Press on behalf of the History of Science Society.
- 769 26. Hamill, Patrick. (2014) *A Student's Guide to Lagrangians and Hamiltonians* (p 16). Cambridge University
770 Press, Cambridge, England ISBN 978-1107617520
- 771 27. Leibniz, Gottfried. *Discours de metaphysique*, in *Die Philosophische Schriften von Gottfried Wilhelm Leibniz*, ed. C.
772 I. Gerhardt, 7 vols. (Berlin, 1875-1890), Vol. IV, pp. 442, 443. English translation in Loemker, Vol. I, pp. 464-506.
773 ISBN 0-87220-132-5
- 774 28. Cardwell, D.S.L. (1971) *From Watt to Clausius: The Rise of Thermodynamics in the Early Industrial Age*.
775 Iowa State University Press, Iowa City, Iowa ISBN 978-0801406782
- 776 29. Maupertuis, Pierre (1744) (translated from French by Wikisource; trans. Willow, W) *Accord between*
777 *different laws of Nature that seemed incompatible. (Accord de diferentes loix de la nature qui avoient*
778 *jusqu'ici paru incompatibles)*. Retrieved from
779 [https://en.wikisource.org/wiki/Translation:Accord between different laws of Nature that seemed incompat](https://en.wikisource.org/wiki/Translation:Accord_between_different_laws_of_Nature_that_seemed_incompat)
780 [ible](https://en.wikisource.org/wiki/Translation:Accord_between_different_laws_of_Nature_that_seemed_incompat)
-
- 781 30. Maupertuis, Pierre (1746) (translated from French by Wikisource. trans. Willow, W) *Derivation of the laws*
782 *of motion and equilibrium from a metaphysical principle. (Les loix du mouvement et du repos déduites d'un principe*
783 *metaphysique)*
784 Retrieved from "https://en.wikisource.org/w/index.php?
785 title=Translation:Derivation_of_the_laws_of_motion_and_equilibrium_from_a_metaphysical_principle&oldid
786 =6521847"

- 787 31. Coopersmith, Jennifer (2017) *The Lazy Universe: An Introduction to the Principle of Least Action*. Oxford
788 University Press, Oxford, England ISBN 978-0198743040
- 789 32. Carnot, Lazare. (2015) *Reflexions On the Metaphysical Principles of the Infinitesimal Analysis*. Andesite
790 Press ISBN 978-1298721525
- 791 33. Zahar, Elle (2001) *Poincare's Philosophy: From Conventionalism to Phenomenology*. Open Court
792 Publishing, Chicago Illinois ISBN 978-0812694352
- 793 34. Lakatos, Imre (1978) *The Methodology of Scientific Research Programmes: Volume 1*. Cambridge
794 University Press, Cambridge England ISBN 0-521-21644-3
- 795 35. Herbert, Nick (1985) *Quantum Realism: Beyond the New Physics*. Anchor Press, Doubleday, Garden City,
796 New York ISBN 0-385-18704-1
- 797• 36. Schilpp, Arthur (author, editor) (1959) *Albert Einstein: Philosopher-Scientist, Volume 1, (p 81)*, Harper
798 Touchbooks/Harper Brothers, New York, London ASIN: B000QAXADI
- 799 37. Pauli, Wolfgang (2010) (Edited by Charles Enz and Karl von Meyenn; translated by Robert Schlapp)
800 Wolfgang Pauli: *Writings on Physics and Philosophy (p32-34)*. Springer-Verlag, Berlin, Heidelberg, New York
801 ISBN 978-3642081637
- 802• 38. De Broglie, Louis (1953) *The Revolution in Physics: A Non-mathematical Survey of Quanta*. The Noonday
803 Press (Farrar, Straus & Cudaby) New York ASIN: B0007HDM8I
- 804 39. Kuhn, Thomas (1978) *Black-Body Theory and the Quantum Discontinuity, 1894-1912 Radiation*. University
805 of Chicago Press, Chicago ISBN 978-0226458007
- 806 40. Gribbin, John (2013) *Erwin Schrodinger and the Quantum Revolution*. Wiley, Hoboken New Jersey ISBN
807 978-1118299265
- 808 41. Greenspan, Nancy Thorndike (2005) *The End of the Certain World: The Life and Science of Max Born*. Basic
809 Books, New York ISBN 978-0470856635
- 810 42. Drago, Antonino (2007) *There exist two models of organization of a scientific theory*. *Atti della della*
811 *Fondazione Ronchi* 62(6):839–856
- 812• 43. Barrow, John (2001). *The Book of Nothing: Vacuums, Voids, and the Latest Ideas about the Origins of the*
813 *Universe*. Pantheon Books, New York ASIN: B01FKTEZ9M
- 814• 44. Maupertuis, Pierre (1745, 2012) *Venus physique*. Hachette Livre, Paris, France ASIN: B01K91AN4M
- 815 45. Maupertuis, Pierre (1751, 2011) *Essais de Cosmologie*. Nabu Press, Charleston, South Carolina ISBN 978-
816 1246582734
- 817 46. Wheeler, John Archibald (1994) *At Home in the Universe*. American Institute of Physics, College Park,
818 Maryland ISBN 978-0195095999
- 819 47. Stapp, Henry (2011) *Mindful Universe: Quantum Mechanics and the Participating Observer*. Springer.
820 Heidelberg, Berlin, New York ISBN 978-3642180750

- 821 48. Whitehead, Alfred North (1969) *Process and Reality: An Essay of Cosmology*. Free Press, New York ISBN
822 978-0029345702
- 823 49. Plato and DJ Zeyl. (2000) *Timaeus*. Hackett Publishing Company, Indianapolis, Indiana, ISBN 978-
824 0872204461
- 825 50. Zeyl, Donald and Sattler, Barbara, "Plato's *Timaeus*", *The Stanford Encyclopedia of Philosophy* (Winter 2017
826 Edition), Edward N. Zalta (ed.), URL = <<https://plato.stanford.edu/archives/win2017/entries/plato-timaeus/>>.
- 827 51. Baggott, Jim (2014) *Farewell to Reality: How Modern Physics Has Betrayed the Search for Scientific Truth*.
828 Pegasus Books, New York ISBN 978-1605985749
- 829 52. Susskind, Leonard (2006) *The Cosmic Landscape: String Theory and the Illusion of Intelligent Design*. Back
830 Bay Books, New York ISBN 978-0739473115
- 831 53. Carroll, Sean (2012) *Mysteries of Modern Physics: Time*. The Great Courses. The Teaching Company,
832 Chantilly, Virginia ISBN 978-1598038705
- 833 54. Albert, David Z (2003) *Time and Chance*. Harvard University Press, Cambridge University Press ISBN 978-
834 0674011328
- 835 55. Carroll, Sean (2016) *The Big Picture: On the Origins of Life, Meaning, and the Universe Itself*. Dutton, Boston
836 MA ISBN 978-0-52-954828
- 837 56. Smolin, Lee (2006) *The Trouble with Physics: The Rise of String Theory, The Fall of Science, and What
838 Comes Next*. Houghton Mifflin Harcourt, Boston, MA, New York ISBN 978-0618918683
- 839 57. Smolin, Lee (2013) *Time Reborn: From the Crisis in Physics to the Future of the Universe*. Houghton Mifflin
840 Harcourt, Boston MA ISBN 978-0544245594
- 841 58. Smolin, Lee (2009) "Informal Chalk and Talk" [Perimeter Institute Recorded Seminar Archive](http://pirsa.org/09080032/).
842 <http://pirsa.org/09080032/> Perimeter Institute, Waterloo Canada
- 843 59. West, Geoffrey (2017) *Scale: The Universal Laws of Life, Growth, and Death in Organisms, Cities, and
844 Companies*. Penguin Books, City of Westminster, London, England ISBN 978-0143110903