

Annotated Bibliography for *Computational Foundations for the Second Law of Thermodynamics*

Stephen Wolfram

For an extensive discussion of the history of the Second Law, see:

S. Wolfram (2023), “How Did We Get Here? The Tangled History of the Second Law of Thermodynamics”. writings.stephenwolfram.com/2023/01/how-did-we-get-here-the-tangled-history-of-the-second-law-of-thermodynamics.

For a discussion of the personal and other background history of this work, see:

S. Wolfram (2023), “A 50-Year Quest: My Personal Journey with the Second Law of Thermodynamics”. writings.stephenwolfram.com/2023/02/a-50-year-quest-my-personal-journey-with-the-second-law-of-thermodynamics.

Pointers to specific references are included as hyperlinks in the online version of this piece.

Development of the Approach Described Here

The concept of computational irreducibility was described in:

S. Wolfram (1985), “Undecidability and Intractability in Theoretical Physics”, *Physical Review Letters* 54, 735–738. content.wolfram.com/undecidability-intractability-theoretical-physics.pdf.

An early description of the computational character of the Second Law was given in:

S. Wolfram (1985), “Origins of Randomness in Physical Systems”, *Physical Review Letters* 55, 449–452. content.wolfram.com/origins-randomness-physical-systems.pdf.

Further development was done in:

S. Wolfram (2002), “Irreversibility and the Second Law of Thermodynamics”, in *A New Kind of Science*, Wolfram Media, 441–457. wolframscience.com/nks/chap-9--fundamental-physics/#sect-9-3--irreversibility-and-the-second-law-of-thermodynamics.

The Wolfram Physics Project is described in:

S. Wolfram (2020), “A Class of Models with the Potential to Represent Fundamental Physics”. [arXiv:2004.08210](https://arxiv.org/abs/2004.08210).

The “particle cellular automaton” used here was introduced in:

S. Wolfram (1986), “Minimal Cellular Automaton Approximations to Continuum Systems”, presented at *Cellular Automata '86*; reprinted in *Cellular Automata and Complexity: Collected Papers* (2019), Addison-Wesley. content.wolfram.com/cellular-automaton-continuum-systems.pdf.

Other Works on the Second Law

Classic Original Sources

S. Carnot (1824), *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance* (in French), Bachelier. [ark:/13960/t7rn68p52](https://arxiv.org/abs/13960/t7rn68p52). (Translated by R. Thurston (1890), as *Reflections on the Motive Power of Heat*, reprinted in *Reflections on the Motive Power of Fire* (1988), Dover. [ark:/13960/t0jv2661s](https://arxiv.org/abs/13960/t0jv2661s).)

R. Clausius (1857), “Über die Art der Bewegung die wir Wärme nennen” (in German), *Annalen der Physik* 100, 353–380. [ark:/13960/t9679978p](https://arxiv.org/abs/13960/t9679978p). (Translated as “On The Nature of the Motion which we call Heat”, *Philosophical Magazine* 14, 108–127 (1857). [ark:/13960/t3jw8w07q](https://arxiv.org/abs/13960/t3jw8w07q).)

J. Maxwell (1858), “Illustrations of the Dynamical Theory of Gases”, *Philosophical Magazine* 19, 19–32. [ark:/13960/t4sj20460](https://arxiv.org/abs/13960/t4sj20460).

J. Maxwell (1866), “On the Dynamical Theory of Gases”, *Philosophical Transactions of the Royal Society of London* 157, 49–88. [ark:/13960/t06x5c78d](https://arxiv.org/abs/13960/t06x5c78d).

L. Boltzmann (1872), “Weitere Studien über das Wärmegleichgewicht unter Gasmolekülen” (in German), *Sitzungsberichte Akademie der Wissenschaften* 66, 275–370. [ark:/13960/t4pk0sf66](https://arxiv.org/abs/13960/t4pk0sf66). (Translated as “Further Studies on the Thermal Equilibrium of Gas Molecules”, in *The Kinetic Theory of Gases: An Anthology of Classic Papers with Historical Commentary* (2003), S. Brush (ed.), Imperial College Press, 262–349. [doi: 10.1142/p281](https://doi.org/10.1142/p281).)

W. Thomson (1874), “The Kinetic Theory of the Dissipation of Energy”, *Proceedings of the Royal Society of Edinburgh* 8, 325–334. [ark:/13960/t2b85fc5t](https://arxiv.org/abs/13960/t2b85fc5t).

L. Boltzmann (1877), “Über die Beziehung zwischen dem zweiten Hauptsatze der mechanischen Wärmetheorie und der Wahrscheinlichkeitsrechnung respective den Sätzen über das Wärmegleichgewicht” (in German), *Sitzungsberichte Akademie der Wissenschaften* 76, 373–435. [doi: 10.1017/CBO9781139381437.011](https://doi.org/10.1017/CBO9781139381437.011). (Translated as “On the Relationship between the Second Fundamental Theorem of the Mechanical Theory of Heat and Probability Calculations Regarding the Conditions for Thermal Equilibrium”, *Entropy* 17, 1971–2009 (2015). [doi: 10.3390/e17041971](https://doi.org/10.3390/e17041971).)

J. Gibbs (1902), *Elementary Principles in Statistical Mechanics*, Charles Scribner’s Sons. [ark:/13960/t6rz5sz8r](https://arxiv.org/abs/13960/t6rz5sz8r).

Notable Collections, etc.

R. Clausius (1864), *Abhandlungen über die mechanische Wärmetheorie* (in German), Friedrich Vieweg und Sohn. [ark:/13960/t53f4qn28](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8). (Translated by W. Browne (1879), as *The mechanical theory of heat*, Macmillan and Co. [ark:/13960/t1wd4fr9c](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8).)

W. Thomson (1882–1911), *Mathematical and physical papers* vols. 1–6, Cambridge University Press. [ark:/13960/t20d2r137](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8).

A. Tuckerman (1890), “Index to the literature of thermodynamics”, *Smithsonian Miscellaneous Collections* 34, iii–239. [repository.si.edu/handle/10088/23167](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8).

W. Niven (ed.) (1890), *The Scientific Papers of James Clerk Maxwell* vols. 1 & 2, Dover. [ark:/13960/t3pv6kt6d](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8).

F. Hasenöhr (ed.) (1909), *Wissenschaftliche Abhandlungen von Ludwig Boltzmann* (in German) [*Scientific Works of Ludwig Boltzmann*] vols. 1–3, Johann Ambrosius Barth. (Available on HathiTrust.)

F. Donnan and A. Haas (eds.) (1936), *A Commentary on the Scientific Writings of J. Willard Gibbs* vols. 1 & 2, Yale University Press. [ark:/13960/t6sx6c24j](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8).

J. Stachel, D. Cassidy, J. Renn and R. Schulmann (eds.) (1990), *The Collected Papers of Albert Einstein* vol. 2, Princeton University Press. [einsteinpapers.press.princeton.edu/vol2-doc](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8).

H. Ebbinghaus, C. Fraser and A. Kanamori (eds.) (2010), *Ernst Zermelo - Collected Works/Gesammelte Werke* vols. 1 & 2, Springer. doi: 10.1007/978-3-540-79384-7.

Notable Textbooks

J. Maxwell (1871), *Theory of Heat*, Longmans, Green, and Co. (Available on Wikimedia.org.) (Reprinted as *Theory of Heat* (1872), D. Appleton and Co. [ark:/13960/t26976m7w](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8).)

L. Boltzmann (1896), *Vorlesungen über Gastheorie* (in German), Johann Ambrosius Barth. [ark:/13960/t18k7bb6k](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8). (Translated by S. Brush (1995), as *Lectures on Gas Theory*, Dover. [ark:/13960/t40s8nn1q](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8).)

M. Planck (1897), *Vorlesungen über Thermodynamik* (in German), Veit & Comp. [ark:/13960/t1hh6k62v](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8). (Translated by A. Ogg (1905), as *Treatise On Thermodynamics* 3rd edition, Dover. [ark:/13960/t06x4mn0f](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8).)

J. Jeans (1904), *The Dynamical Theory of Gases*, Cambridge University Press. [ark:/13960/t8pc2w43r](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8).

P. Ehrenfest and T. Ehrenfest (1912), “Begriffliche Grundlagen der Statistischen Auffassung in der Mechanik” (in German), *Encyklopädie der mathematischen Wissenschaften* 4, part 4, 1–90. [lorentz.leidenuniv.nl/IL-publications/sources/Ehrenfest_1911b.pdf](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8). (Translated by M. Moravcsik (1959), as *The Conceptual Foundations of the Statistical Approach in Mechanics*, Cornell University Press. [ark:/13960/t8jf2nx05](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8).)

L. Landau and E. Lifshitz (1938), *Statisticheskaya fizika* (in Russian). (Translated by E. Peierls and R. Peierls (1958), as *Statistical Physics*, Pergamon Press. [ark:/13960/t07x01p71](https://nbn-resolving.org/urn:nbn:de:hbz:5:1-33333-p0028-8).)

- R. Tolman (1938), *The Principles of Statistical Mechanics*, Oxford University Press. [ark:/13960/t9w11hx7r](https://doi.org/10.1093/oxfordhb/9780198501734/0000001).
- A. Sommerfeld (1956), *Thermodynamics and Statistical Mechanics*, Academic Press. [ark:/13960/t53g3bb8j](https://doi.org/10.1007/978-1-4613-0173-4).
- H. Callen (1960), *Thermodynamics: An Introduction to the Physical Theories of Equilibrium Thermostatics and Irreversible Thermodynamics*, Wiley & Sons. [ark:/13960/t77t65w24](https://doi.org/10.1002/9781118013263).
- K. Huang (1963), *Statistical Mechanics*, Wiley & Sons. [ark:/13960/t14n0bb0g](https://doi.org/10.1002/9781118013263).
- F. Reif (1965), *Statistical Physics*, McGraw Hill Company. [ark:/13960/t44q8ww6q](https://doi.org/10.1002/9781118013263).
- D. Ruelle (1969), *Statistical Mechanics: Rigorous Results*, Imperial College Press. [ark:/13960/t6rz72b6s](https://doi.org/10.1002/9781118013263).
- L. Landau and E. Lifshitz (1981), *Physical Kinetics*, Pergamon Press. [ark:/13960/t20d2fj56](https://doi.org/10.1002/9781118013263).
- G. Gallavotti (1999), *Statistical Mechanics: A Short Treatise*, Springer. doi: 10.1007/978-3-662-03952-6.

Surveys about Foundations

- P. Bridgman (1941), *The Nature of Thermodynamics*, Harvard University Press. [ark:/13960/t7vm43w9f](https://doi.org/10.1002/9781118013263).
- H. Reichenbach (1956), *The Direction of Time*, University of California Press. [ark:/13960/t8sc1wj45](https://doi.org/10.1002/9781118013263).
- P. Landsberg (1956), “Foundations of Thermodynamics”, *Reviews of Modern Physics* 28, 363–392. doi: 10.1103/RevModPhys.28.363.
- E. Cohen (1962), *Fundamental Problems in Statistical Mechanics*, North-Holland.
- E. Jaynes (1965), “Gibbs vs Boltzmann Entropies”, *American Journal of Physics* 33, 391–398. doi: 10.1119/1.1971557.
- O. Penrose (1970), *Foundations of Statistical Mechanics: A Deductive Treatment*, Dover.
- P. Davies (1977), *The Physics of Time Asymmetry*, University of California Press. [ark:/13960/t5n99zw8p](https://doi.org/10.1002/9781118013263).
- C. Bennett (1987), “Demons, Engines and the Second Law”, *Scientific American* 257, 108–117. doi: 10.1038/SCIENTIFICAMERICAN1187-108.
- M. Mackey (1992), *Time’s Arrow: The Origins of Thermodynamic Behavior*, Springer. doi: 10.1007/978-1-4613-9524-9.
- J. Lebowitz (1993), “Macroscopic laws, microscopic dynamics, time’s arrow and Boltzmann’s entropy”, *Physica A* 194, 1–27. doi: 10.1016/0378-4371(93)90336-3.
- J. Halliwell (1996), *Physical Origins of Time Asymmetry*, Cambridge University Press.
- L. Schulman (1997), *Time’s Arrows and Quantum Measurement*, Cambridge University Press. doi: 10.1017/CBO9780511622878.
- R. Peierls (1997), “Time reversal and the second law of thermodynamics”, in *Selected*

Scientific Papers of Sir Rudolf Peierls, R. Dalitz and R. Peierls (eds.), World Scientific, 563–570. doi: 10.1142/9789812795779_0055.

J. Uffink (2001), “Bluff Your Way in the Second Law of Thermodynamics”, *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 32, 305–394. arXiv:cond-mat/0005327.

J. Uffink (2007), “Compendium of the foundations of classical statistical physics”, in *Philosophy of Physics, Handbook of the Philosophy of Science*, J. Butterfield and J. Earman (eds.), Elsevier, 923–1074.

W. Grandy Jr. (2008), *Entropy and the Time Evolution of Macroscopic Systems*, Oxford University Press.

J. Parrondo, J. Horowitz and T. Sagawa (2015), “Thermodynamics of information”, *Nature Physics* 11, 131–139. doi: 10.1038/nphys3230.

D. Lairez (2022), “What Entropy Really Is: the Contribution of Information Theory”. arXiv:2204.05747.

Historical Surveys & Collections

J. Kestin (ed.) (1976), *The Second Law of Thermodynamics*, Cambridge University Press.

S. Brush (1976), *The Kind of Motion We Call Heat: A History of the Kinetic Theory of Gases in the Nineteenth Century* vols. 1 & 2, North-Holland.

J. Kestin (ed.) (1977), *The Second Law of Thermodynamics*, Dowden, Hutchinson and Ross.

C. Truesdell (1980), *The Tragicomical History of Thermodynamics, 1822–1854*, Springer. archive.org/details/tragicomicalhist0000unse.

E. Jaynes (1984), *The Evolution of Carnot’s Principle*, Springer. doi: 10.1007/978-94-009-3049-0_15.

J. Plato (1991), “Boltzmann’s Ergodic Hypothesis”, *Archive for History of Exact Sciences* 42, 71–89. doi: 10.1007/BF00384333.

S. Brush (ed.) (2003), *The Kinetic Theory of Gases: An Anthology of Classic Papers with Historical Commentary*, Imperial College Press. doi: 10.1142/p281.

I. Müller (2006), *A History of Thermodynamics: The Doctrine of Energy and Entropy*, Springer.

SklogWiki (2007–). sklogwiki.org (website).

H. Leff and Andrew Rex (eds.) (2016), *Maxwell’s Demon: Entropy, Information, Computing*. Princeton University Press.

O. Darrigol (2018), *Atoms, Mechanics, and Probability: Ludwig Boltzmann’s Statistico-Mechanical Writings – An Exegesis*, Oxford University Press.

Less Technical Presentations

J. Maxwell (1878), “Atom”, “Attraction”, “Constitution of bodies”, “Diagrams”, “Ether”, “Molecule”, *Encyclopedia Britannica* 9th edition. [ark:/13960/s22210225hh](https://doi.org/10.1093/0110225hh). (Reprinted in *The Scientific Papers of James Clerk Maxwell* vol. 2 (1890). [ark:/13960/t56f4vm7t](https://doi.org/10.1093/0110225hh).)

H. Helmholtz (1885), *Popular Lectures on Scientific Subjects*, Appleton and Company. [urn:oclc:record:669327403](https://nbn-resolving.org/urn:oclc:record:669327403).

L. Boltzmann (1895), *Theoretical Physics and Philosophical Problems: Selected Writings*, D. Reidel Publishing Company.

E. Schrödinger (1945), *What is Life? The Physical Aspect of the Living Cell*, The Macmillan Company. [ark:/13960/t4qk7tk6c](https://doi.org/10.1093/0110225hh).

H. Bent (1965), *The Second Law: An Introduction to Classical and Statistical Thermodynamics*, Oxford University Press. [ark:/13960/t1gj7793z](https://doi.org/10.1093/0110225hh).

P. Atkins (1984), *The Second Law*, Freeman and Company. [ark:/13960/t2h78530v](https://doi.org/10.1093/0110225hh).

S. Berry (2019), *Three Laws of Nature: A Little Book on Thermodynamics*, Yale University Press.