Notes on the Dynamics of Disorder

On the Fluctuations of Dissipation: An Annotated Bibliography*

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Origins: Fluctuation theorem: Evans et al. (1993) [39]. Evans-Searles fluctuation theorem: Evans and Searles (1994) [41]. Gallavotti-Cohen fluctuation theorem: Gallavotti and Cohen (1995) [43]. Fluctuation theorem, first use of terminology: Gallavotti and Cohen (1995) [44]. Jarzynski equality: Jarzynski (1997) [50]. Crooks fluctuation theorem: Crooks (1999) [75]. Hatano-Sasa fluctuation theorem: Hatano and Sasa (2001) [99]. Feedback Jarzynski equality: Sagawa and Ueda (2010) [371].

Reviews and expositions: For a gentle, modern introduction see Spinney and Ford (2013) [458], and then try reading some of the other reviews in the same volume: Sagawa and Ueda (2013) [457], Reid et al. (2013) [456], Gaspard (2013) [453]. See also Evans and Searles (2002) [118], Harris and Schütz (2007) [290], Seifert (2012) [438], Van den Broeck and Esposito (2015) [471]. For reviews and expositions of non-equilibrium single-molecule experiments see Hummer and Szabo (2005) [203], Bustamante et al. (2005) [202], Ritort (2006) [249], Ritort (2008) [344]. Other books, reviews, and expositions: Crooks (1999) [80], Seifert (2008) [331].

Foundations – Thermodynamics and statistical mechanics Efficiency of heat engines and the foundation of thermodynamics: Carnot (1824) [1]; First law of thermodynamics: von Helmholtz (1847) [2]; Second law of thermodynamics Thomson (Lord Kelvin) [3], Clausius (1865) [4]; Entropy: Clausius (1865) [4]; Statistical definition of entropy: Boltzmann (1872) [6], Boltzmann (1898) [8], Planck (1901) [9], Gibbs (1902) [10], Shannon (1948) [22], Jaynes (1957) [23], Jaynes (1957) [24]; Foundations of statistical mechanics: Maxwell (1871) [5], Boltzmann (1896) [7], Boltzmann (1898) [8], Gibbs (1902) [10].

*Massively incomplete, hopelessly out-of-date, and only occasionally updated.

Foundations – Microscopic reversibility and detailed balance: Origins: Tolman (1924) [11], Dirac (1924) [12], Tolman (1925) [14], Lewis (1925) [13], Fowler and Milne (1925) [15]. Discussion: Onsager (1931) [18], Tolman (1938) [20], Crooks (1998) [57], Crooks (2011) [402].

Experiments: Single molecule Jarzynski: Liphardt et al. (2002) [113]; single molecule fluctuation theorems: Collin et al. (2005) [209], Ritort (2006) [249]; dragged optically trapped colloid particle: Wang et al. (2002) [114], Wang et al. (2005) [190], Wang et al. (2005) [215]; Hatano and Sasa with optically trapped colloid particle: Trepagnier et al. (2004) [165]; optically trapped colloid particle, time varying spring constant: Carberry et al. (2004) [144], Carberry et al. (2004) [166]; colloidal particle in periodic potential: Speck et al. (2007) [294]; colloidal particle in viscoelastic media: Carberry et al. (2007) [289]; colloidal particle in time dependent non-harmonic potential: Blickle et al. (2006) [230], Speck et al. (2007) [294]; two level system: Schuler et al. (2005) [195]; turbulent flow: Ciliberto et al. (2004) [158]; electric circuit: Garnier and Ciliberto (2005) [199], Andrieux et al. (2008) [306]; mechanical oscillator: Douarche et al. (2005) [198], Douarche et al. (2005) [210]; bit erasure, colloidal particle: Bérut et al. (2012) [421]; theory and discussion: Hummer and Szabo (2001) [96].

Analytic model systems: (Model systems for which the work distributions can be computed analytically) Harmonic potentials: Mazonka and Jarzynski (1999) [81]; two level systems: Ritort et al. (2002) [117], Ritort (2004) [163]; ideal gas compression: Lua and Grosberg (2005) [185], Lua (2005) [224], Bena et al. (2005) [208], Pressé and Silbey (2006) [235] and effusion: Cleuren et al. (2006) [251]; Gaussian polymer chains: Speck and Seifert (2005) [184], Dhar (2005) [183], Imparato and Peliti (2005) [180], Pressé and Silbey (2006) [235]; Joule experiments: Cleuren et al. (2006) [231], adiabatically stretched rotors: Bier (2005) [213]; charged particles in magnetic fields: Jayannavar and Sahoo (2006) [239]; adiabatic compression of a dilute gas: Crooks and Jarzynski (2007) [271];

Simulations of work distributions:

- two-dimensional Ising model: Chatelain and Karevski (2006) [245]
- fluctuating lattice Boltzmann model: Chari et al. (2012) [427]

Bochkov-Kuzovlev generalized fluctuation-dissipation theorem: Origins: Bochkov and Kuzovlev (1977) [32], Bochkov and Kuzovlev (1979) [33], Bochkov and Kuzovlev (1981) [34], Bochkov and Kuzovlev (1981) [35]. Summary: Stratonovich (1994) [42]. Relation to Jarzynski equality and fluctuation theorems: Jarzynski (2007) [287], Horowitz and Jarzynski (2008) [328], Pitaevskii (2011) [400].

Jarzynski equality: Origins: Jarzynski (1997) [50], Jarzynski (1997) [55], Crooks (1998) [57]. Connection to fluctuation theorems: Crooks (1999) [75], Crooks (2000) [84]. Strong coupling: Jarzynski (2004) [159].

Gallavotti-Cohen Fluctuation theorem Origins: Gallavotti and Cohen (1995) [43], Gallavotti and Cohen (1995) [44] Discussion: Gallavotti (1999) [475], Cohen and Gallavotti (1999) [74] Simulations: Bonetto et al. (1998) [64]

Multivariant fluctuation theorems: García-García et al. (2010) [376], García-García et al. (2012) [419], Sivak et al. (2013) [445]

Excess free energy: The connection between the excess free energy of nonequilibrium ensembles and relative entropy seems to have been independently rediscovered multiple times. Bernstein and Levine (1972) [30] (Eqs. 44 and 54) defined an "entropy deficiency" as the relative entropy of a nonequilibrium to canonical equilibrium. Shaw (1984) [36] p37 states that available free energy is the relative entropy, but without detailed discussion. Gaveau and Schulman (1997) [53] p348 notes that the relative entropy to equilibrium state is a generalized free energy, but again without much discussion. Qian (2001) [98] provides a detailed discussion of the definition of free energy away from equilibrium and its expression as a relative entropy. Hatano and Sasa (2001) [99] discuss the generalization of free energy out of equilibrium and a generalized minimum work principle for steady states. The connection between excess free energy and reversible work is shown in Vaikuntanantan et al (2009) Vaikuntanathan and Jarzynski (2009) [359] using a Jarzynski equality like argument. The instantaneous stabilization procedure for (in principle) extracting the reversible (maximum) work is detailed in Hasegawa et al. (2010) [383], Takara et al. (2010) [385] and further discussed in Esposito and Van den Broeck (2011) [405]. Further discussion and consequences of this interrelation can be found in Sivak and Crooks (2012) Sivak and Crooks (2012) [429] and Deffner et al (2012) Deffner and Lutz (2012) [440].

Dissipation and the relative entropy between conjugate trajectory ensembles: A good discussion of this relation is found in: Kawai et al. (2007) [272]. See also: Gaspard (2004) [148], Gaspard (2004) [167], Jarzynski (2006) [243], Kawai et al. (2007) [272], Gomez-Marin et al. (2008) [317], Andrieux et al. (2008) [306], Feng and Crooks (2008) [327], Horowitz and Jarzynski (2009) [348], Parrondo et al. (2009) [354], Jarzynski (2011) [393]

Feedback control: Origins: Sagawa and Ueda (2010) [371]; Generalized Jarzynski (Single loop feedback): Sagawa and Ueda (2010) [371]; Experiments: Toyabe et al. (2010) [386]; Multi-loop feedback: Horowitz and Vaikuntanathan (2010) [384], Fujitani and Suzuki (2010) [381].

Time's Arrow: Origin of term: Eddington (1928) [16]; Useful philosophical discussions: Price (1996) [49], Albert (2000) [93]. Past hypothesis: Albert (2000) [93]. Length of: Feng and Crooks (2008) [327].

Work and heat The microscopic definition of work was discussed by Gibbs (1902) [10] (Pages 42-35) and Schrödinger (1946) [21] (See the paragraphs found between Eqs. 2.13 and 2.14). However, the importance of this viewpoint was not appreciated until advances in simulation and experimentation made it necessary to carefully contemplate performing controlled perturbations of single, microscopic systems. The microscopic definition of work was also discussed by: Hunter et al. (1993) [40], Jarzynski (1997) [50], Crooks (1998) [57], Sekimoto (1997) [51], Sekimoto (1998) [60] and further developed in Jarzynski (1997) [55], Jarzynski (1998) [61], Crooks (1999) [75], Hendrix and Jarzynski (2001) [100], Sekimoto (2010) [391]. Another clear exposition with a discussion of thermodynamic consistency is found in: Peliti (2008) [329]. See also Narayan and Dhar (2004) [139], Imparato et al. (2007) [302].

Maxwell's demon

- Reviews: Leff and Rex (2003) [136]
- Origin: Maxwell (1871) [5]
- Szilárd engine: Szilárd (1929) [17]

Stochastic thermodynamics Origin of term: Van den Broeck (1986) [37], Mou et al. (1986) [38]

Chronological Bibliography

★ Great papers that have been, will be, or should be influential.

[1] Sadi Carnot. *Réflexions sur la puissance motrice du feu et sur les machines propres a développer cette puissance*. Chez Bachelier, Libraire, Paris (1824). Reflections on the motive power of fire and machines fitted to develop that power.
- Foundation of thermodynamcs. Heat engines and Carnot efficiency. "The driving power of heat is independent of the agents used to realize it; its value is uniquely fixed by the temperatures of the bodies between which the transfer of caloric is made"

[2] Hermann von Helmholtz. *Über die Erhaltung der Kraft (On the Conservation of Force)*. Druck und Verlag, Berlin (1847). On the Conservation of Force.
- Definitive statement of the conservation of energy (And thereby the first law of thermodynamcis). (Terminology was not yet settled: Helmholtz used the word *force* for what we now call *energy*.)

[3] William Thomson (Lord Kelvin). On the dynamical theory of heat, with numerical results deduced from Mr. Joule's equivalent of a thermal unit, and M. Regnault's observations on steam. *Trans. Roy. Soc. Edin.*, XX (part II):261–268; 289–298 (1851).
- First statement of (essentially) the second law of thermodynamics. "It is impossible, by means of inanimate material agency, to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects."

[4] Rudolf Clausius. Ueber verschiedene für die anwendung bequeme formen der hauptgleichungen der mechanischen wärmetheorie. *Annalen der Physik und Chemie*, 201(7):353–400 (1865). doi:10.1002/andp.18652010702.
- Introduction of the term entropy, and statement of Clausius's form of the second law of thermodynamics. Quote: "We now seek an appropriate name for S . . . . We would call S the transformation content of the body. However I have felt it more suitable to take names of important scientific quantities from the ancient languages in order that they may appear unchanged in all contemporary languages. Hence I propose that we call S the entropy of the body after Greek word . . . meaning "transformation". I have intentionally formed the word entropy to be as similar as possible to the word energy, since the two quantities that are given these names are so closely related in their physical significance that a certain likeness in their names has seemed appropriate."

[5] James C. Maxwell. *Theory of heat*. Appleton, London (1871).
- Invocation of Maxwell's demon.

[6] Ludwig Boltzmann. Weitere studien über das Wärmegleichgewicht unter Gasmolekülen (Further studies on the thermal equilibrium of gas molecules). *Sitzungsberichte Akad. Wiss., Vienna, part II*, 66:275–370 (1872).
- The Boltzmann equation and Boltzmann's H-theorem. First paper on non-equilibrium thermodynamics.

[7] Ludwig Boltzmann. *Vorlesungen über Gastheorie (Lectures on gas theory)*, volume I. J. A. Barth (1896). Translated in [27].

[8] Ludwig Boltzmann. *Vorlesungen über Gastheorie (Lectures on gas theory)*, volume II. J. A. Barth (1898). Translated in [27].

[9] Max Planck. Ueber das gesetz der energieverteilung im normalspectrum (on the law of distribution of energy in the normal spectrum). *Ann. Phys.*, 309(3):553–563 (1901). doi:10.1002/andp.19013090310.
- Origin of the Boltzmann constant, Eq. (3), $S_N = k \ln W +$ const.

[10] J. Willard Gibbs. *Elementary principles in statistical mechanics*. Charles Scribner's Sons, New York (1902).
- Genesis and foundation of modern statistical mechanics. Nonstandard notations: energy: ϵ; temperature: θ; free energy: ψ; index of probability: $\nu \equiv \ln p_x$; entropy: $-\bar{\nu}$. Canonical ensemble (91). Statistical definition of entropy (111) p44. Second law expressed as an average work inequality (481).

[11] Richard C. Tolman. Duration of molecules in upper quantum states. *Phys. Rev.*, 23:693–709 (1924). doi:10.1103/PhysRev.23.69.
- Genesis of "The principle of microscopic reversibility" (p699). Quote: "This assumption should be recognized as a distinct postulate and might be called the principle of *microscopic reversibility*. In the case of a system in thermodynamic equilibrium, the principle would require not only that the total number of molecules leaving a given quantum state in unit time shall equal the number arriving in that state in unit time, but also the the number leaving by any one particular path shall be equal to the number arriving by the reverse of that particular path."

[12] Paul A. M. Dirac. The conditions for statistical equilibrium between atoms, electrons and radiation. *Proc. Rol. Soc. A.*, 106:581–596 (1924).
- Definition and discussion of the "principle of detailed balance".

[13] Gilbert N. Lewis. A new principle of equilibrium. *Proc. Natl. Acad. Sci. U.S.A.*, 11(3):179–183 (1925).
- Quote: "Corresponding to every individual process there is a reverse process, and in a state of equilibrium the average rate of every process is equal to the average rate of its reverse process."

[14] Richard C. Tolman. The principle of microscopic reversibility. *Proc. Natl. Acad. Sci. U.S.A.*, 11(7):436–439 (1925).
- Historical commentary on the principle of microscopic reversibility.

[15] Ralph H. Fowler and E. A. Milne. A note on the principle of detailed balancing. *Proc. Natl. Acad. Sci. U.S.A.*, 11:400–402 (1925).

[16] Arthur S. Eddington. *The nature of the physical world*. Cambridge University Press, Cambridge (1928).
◦ Origin of the phrase "Time's Arrow".

[17] L. Szilárd. Über die entropieverminderung in einem thermodynamischen system bei eingriffen intelligenter wesen (on the reduction of entropy in a thermodynamic system by the intervention of intelligent beings). *Z. Phys.*, 53:840–856 (1929). doi:10.1007/BF01341281.
◦ Origin of Szilárd engine. English translation: [28]

[18] Lars Onsager. Reciprocal relations in irreversible processes. I. *Phys. Rev.*, 37(4):405–426 (1931). doi:10.1103/PhysRev.37.405.
★ ◦ Origin of Onsager's reciprocal relations. Detailed discussion of microscopic reversibility. For experimental verification, see [25].

[19] Lars Onsager. Reciprocal relations in irreversible processes. II. *Phys. Rev.*, 38(12):2265–2279 (1931). doi:10.1103/PhysRev.38.2265.
★ ◦ Onsager regression hypothesis: "...the average regression of fluctuations will obey the same laws as the corresponding macroscopic irreversible process".

[20] Richard C. Tolman. *The principles of statistical mechanics*. Oxford University Press, London (1938).
◦ Comparison of the principles of detailed balance and microscopic reversibility (pp. 163 and 165).

[21] Erwin Schrödinger. *Statistical Thermodynamics*. Cambridge University Press, Cambridge (1946).

[22] Claude E. Shannon. A mathematical theory of communication. *Bell Syst. Tech. J.*, 27:379–423, 623–656 (1948). doi:10.1002/j.1538-7305.1948.tb01338.x.
★ ◦ Foundation of information theory. Latter reprinted in book form with the subtle change in title "The Mathematical Theory of Communication". Entropy; mutual infomration; channel coding theorem; first use of word 'bit' in print.

[23] Edwin T. Jaynes. Information theory and statistical mechanics. *Phys. Rev.*, 106:620–630 (1957). doi:10.1103/PhysRev.106.620.

[24] Edwin T. Jaynes. Information theory and statistical mechanics II. *Phys. Rev.*, 108:171–190 (1957). doi:10.1103/PhysRev.108.171.

[25] Donald G. Miller. Thermodynamics of irreversible processes. The experimental verification of the Onsager reciprocal relations. *Chem. Rev.*, 60:15–37 (1960). doi:10.1021/cr60203a003.

[26] Rolf Landauer. Irreversibility and heat generation in the computing process. *IBM J. Res. Develop.*, 5(3):183–191 (1961). doi:10.1147/rd.53.0183.
★ ◦ Genesis of Landauer's principle: It requires at least $k_B T \ln 2$ (About 3×10^{-21} Joules at 300K) to erase 1 bit of information.

[27] Ludwig Boltzmann. *Lectures on gas theory*. Univ. of Calif. Press (1964). Translation of [7] and [8].

[28] Leo Szilard. On the decrease of entropy in a thermodynamic system by the intervention of intelligent beings. *Behavioral Science*, 9(4):301–310 (1964). doi:10.1002/bs.3830090402.
◦ English translation of [17].

[29] Tomoji Yamada and Kyozi Kawasaki. Nonlinear effects in shear viscosity of critical mixtures. *Prog. Theor. Phys.*, 38(5):1031–1051 (1967). doi:10.1143/PTP.38.1031.
◦ Original reference for the Kawasaki response function.

[30] R. B. Bernstein and R. D. Levine. Entropy and chemical change. I. Characterization of product (and reactant) energy distributions in reactive molecular collisions: Information and entropy deficiency. *J. Chem. Phys.*, 57(1):434–449 (1972). doi:10.1063/1.1677983.

[31] J. Schnakenberg. Network theory of microscopic and macroscopic behavior of master equation systems. *Rev. Mod. Phys.*, 48(4):571–585 (1976). doi:10.1103/RevModPhys.48.571.
★ ◦ Microscopic expression for average entropy production rate (7.6), for continuous time Markov processes.

[32] G. N. Bochkov and Yu. E. Kuzovlev. Contribution to general theory of thermal fluctuations in nonlinear-systems. *Zh. Eksp. Teor. Fiz.*, 72(1):238–247 (1977). [JETP 45, 125 (1977)].

[33] G. N. Bochkov and Yu. E. Kuzovlev. Fluctuation-dissipation relations for nonequilibrium processes in open systems. *Zh. Eksp. Teor. Fiz.*, 76:1071 (1979). [*Sov. Phys. JETP*, 49:543, 1979].

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◦ Bochkov-Kuzovlev generalized fluctuation-dissipation theorem (2.11).

[35] G. N. Bochkov and Yu. E. Kuzovlev. Nonlinear fluctuation-dissipation relations and stochastic models in nonequilibrium thermodynamics: II. Kinetic potential and variational principles for nonlinear irreversible processes. *Physica*, 106(3):480–520 (1981). doi:10.1016/0378-4371(81)90123-0.

[36] Robert Shaw. *The Dripping Faucet as a Model Chaotic System*. Aerial Press, Santa Cruz (1984).

[37] Christian Van den Broeck. Stochastic thermodynamics. In Werner Ebeling and Heinz Ulbricht, editors, *Self organization by Nonlinear Irreversible Processes*, pages 57–61. Springer Berlin Heidelberg, Berlin, Heidelberg (1986). ISBN 978-3-642-71004-9. doi:10.1007/978-3-642-71004-9_6.

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[39] Denis J. Evans, E. G. D. Cohen, and Gary P. Morriss. Probability of second law violations in shearing steady-states. *Phys. Rev. Lett.*, 71(21):3616–3616 (1993). doi:10.1103/PhysRevLett.71.2401. Errata 71(21):2401.

★ ∘ Original exposition of the steady-state fluctuation theorem (8), founded on plausible reasoning and computer simulation. Sheared system with isoenergetic molecular dynamics. Modern era begins. Signs and portents.

[40] John E. Hunter, III, William P. Reinhardt, and Thomas F. Davis. A finite-time variational method for determining optimal paths and obtaining bounds on free energy changes from computer simulations. *J. Chem. Phys.*, 99(9):6856–6864 (1993). doi:10.1063/1.465830.

∘ Explicit microscopic definition of work (7).

[41] Denis J. Evans and Debra J. Searles. Equilibrium microstates which generate second law violating steady-states. *Phys. Rev. E*, 50(2):1645–1648 (1994). doi:10.1103/PhysRevE.50.1645.

★ ∘ Genesis of the Evan-Searles version of the fluctuation theorem for the transient steady state trajectory probabilities in isothermal deterministic molecular dynamics (2). Backed by computer simulation of sheared fluid.

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∘ Section 1.2 contains a concise summary of some of the relevant results of Bochkov and Kuzovlev [34, 35].

[43] Giovanni Gallavotti and E. G. D. Cohen. Dynamical ensembles in nonequilibrium statistical-mechanics. *Phys. Rev. Lett.*, 74(14):2694–2697 (1995). doi:10.1103/PhysRevLett.74.2694.

★ ∘ Genesis of the Gallavotti-Cohen fluctuation theorem for asymptotic steady state fluctuations of the phase space contraction rate in isoenergetic molecular dynamics. Derived from the time reversal symmetry and the chaotic hypothesis.

[44] Giovanni Gallavotti and E. G. D. Cohen. Dynamical ensembles in stationary states. *J. Stat. Phys.*, 80(5-6):931–970 (1995). doi:10.1007/BF02179860.

[45] Denis J. Evans and Debra J. Searles. Steady states, invariant measures, and response theory. *Phys. Rev. E*, 52(6):5839–5848 (1995). doi:10.1103/PhysRevE.52.5839.

[46] Denis J. Evans and Debra J. Searles. Causality, response theory, and the second law of thermodynamics. *Phys. Rev. E*, 53(6):5808–5815 (1996). doi:10.1103/PhysRevE.53.5808.

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★ ∘ First use of the term "Fluctuation theorem".

[48] Giovanni Gallavotti. Extension of Onsager's reciprocity to large fields and the chaotic hypothesis. *Phys. Rev. Lett.*, 77(21):4334–4337 (1996). doi:10.1103/PhysRevLett.77.4334.

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★ ∘ Revelation of the Jarzynski identity (2a). Hamiltonian dynamics. Insights into the nature of work. Cumulant expansion of the Jarzynski identity. Relation to Clausius inequality. Fluctuation-dissipation ratio. Inequalities given a finite number of observations. [Received April 1996, published Jun 1997]

[51] Ken Sekimoto. Kinetic characterization of heat bath and energetics of thermal ratchet models. *J. Phys. Soc. Jpn*, 66(5):1234–1237 (1997). doi:10.1143/jpsj.66.1234.

∘ Insights into thermodynamic work (3) and heat (4) for microscopic systems with stochastic dynamics.

[52] E. G. D. Cohen. Dynamical ensembles in statistical mechanics. *Physica A*, 240(1-2):43–53 (1997). doi:10.1016/S0378-4371(97)00129-5.

[53] Bernard Gaveau and L. S. Schulman. A general framework for non-equilibrium phenomena: the master equation and its formal consequences. *Phys. Lett. A*, 229(6):347–353 (1997). doi:10.1016/S0375-9601(97)00185-0.

∘ Interrelation between relative entropy and free energy out-of-equilibrium (Sec.2).

[54] Pierre Gaspard. Entropy production in open volume-preserving systems. *J. Stat. Phys.*, 88(5-6):1215–1240 (1997). doi:10.1007/BF02732432.

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★ ∘ Further exposition of the Jarzynski identity. Hamiltonian, Langevin, isothermal molecular, and Monte Carlo dynamics. Relation to thermodynamic integration and perturbation. Free energy-work inequality chain.

[56] Ken Sekimoto and Shin-ichi Sasa. Complementarity relation for irreversible process derived from stochastic energetics. *J. Phys. Soc. Jpn*, 66(11):3326–3328 (1997). doi:10.1143/JPSJ.66.3326.

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★ ○

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★ ○ Transient fluctuation theorem for Langevin dynamics driven by non-conservative forces (3.7).

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★ ○ Stochastic energetics. Expressions for heat and work along trajectories of Langevin dynamics.

[61] Christopher Jarzynski. Equilibrium free energies from nonequilibrium processes. *Acta. Phys. Pol. B*, 29(6):1609–1622 (1998).
○ Insights into the nature of work and the driving of a system by an externally controllable parameter.

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○ Numerical evidence in a simulation of 2D sheared particle flow for the Gallavotti-Cohen style phase space contraction rate fluctuation theorem [43].

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★ ○

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○ Entropy production in systems described by Anosov maps.

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I got another quarter hundred weight of books on the subject last night. I have not read them all through.

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