On the Use and Abuse of THERMODYNAMIC Entropy in Physics and Elsewhere

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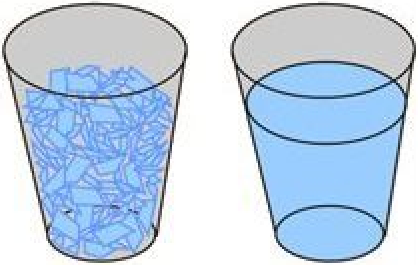
P. Hänggi, S. Hilbert and J. Dunkel, Phil.Trans. Roy. Soc. A **374**, 20150039 (2016)


NEW YORKER

Which is more disordered? The glass of ice chips or the glass of water?



COMMUNICATIONS ON PURE AND APPLIED MATHEMATICS, VOL. XIV, 323-354 (1961)

K. O. Friedrichs anniversary issue

The Many Faces of Entropy*

HAROLD GRAD

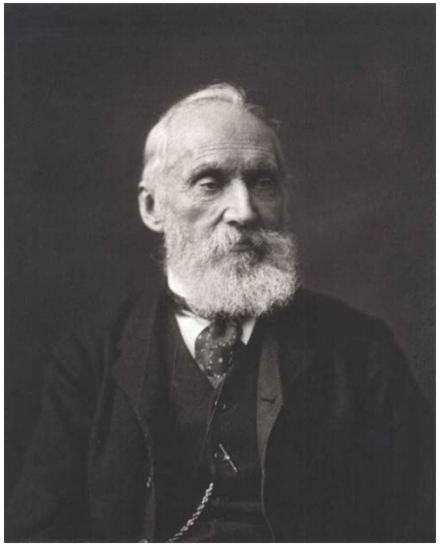
The proper choice will depend on the interests of the individual, the particular phenomena under study, the degree of precision available or arbitrarily decided upon, or the method of description which is employed; and each of these criteria is largely subject to the discretion of the individual.

Second Law

Rudolf Julius Emanuel Clausius
(1822 – 1888)

Heat generally cannot spontaneously flow from a material at lower temperature to a material at higher temperature.

$$\delta Q = T\mathrm{d}S \quad (\text{Zürich, } 1865)$$



William Thomson alias Lord Kelvin
(1824 – 1907)

No cyclic process exists whose sole effect is to extract heat from a single heat bath at temperature T and convert it entirely to work.

The famous Laws

Equilibrium Principle -- minus first Law

An isolated, macroscopic system which is placed in an arbitrary initial state within a finite fixed volume will attain a unique state of equilibrium.

Second Law (Clausius)

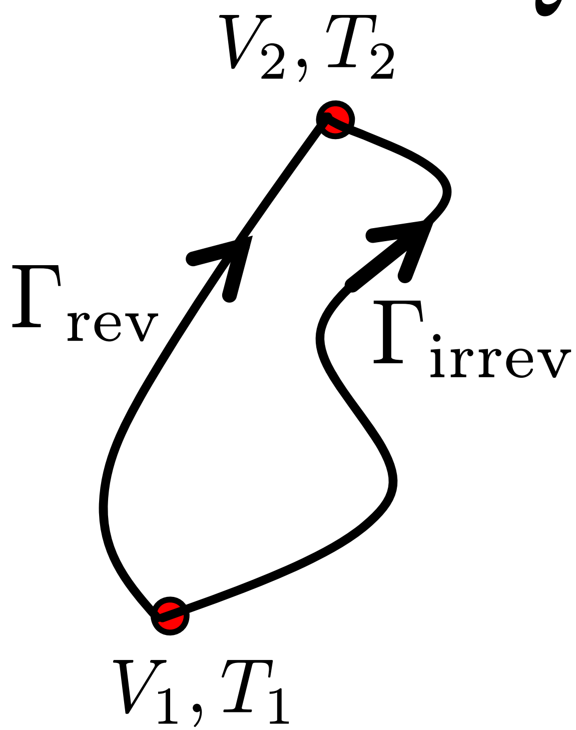
For a non-quasi-static process occurring in a thermally isolated system, the entropy change between two equilibrium states is non-negative.

Second Law (Kelvin)

No work can be extracted from a closed equilibrium system during a cyclic variation of a parameter by an external source.

Entropy S – content of *transformation* „Verwandlungswert“

$$dS = \delta Q^{\text{rev}} / T \, ; \qquad \delta Q^{\text{irrev}} < \delta Q^{\text{rev}}$$



$$\oint_C \frac{\delta Q}{T} \leq 0$$

$$C = \Gamma_{\text{rev}} + \Gamma_{\text{irrev}}^{-1}$$

$$\left. \begin{aligned} S(V_2, T_2) - S(V_1, T_1) &\geq \int_{\Gamma_{\text{irrev}}} \frac{\delta Q}{T} \\ S(V_2, T_2) - S(V_1, T_1) &= \int_{\Gamma_{\text{rev}}} \frac{\delta Q^{\text{rev}}}{T} \end{aligned} \right\} \quad \frac{\partial S}{\partial t} \geq 0 \qquad \textbf{NO !}$$

SECOND LAW

Quote by Sir Arthur Stanley Eddington:

“If someone points out to you that your pet theory of the universe is in disagreement with Maxwell’s equations – then so much the worse for Maxwell’s equations. If it is found to be contradicted by observation – well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.“

Freely translated into German:

Falls Ihnen jemand zeigt, dass Ihre Lieblingstheorie des Universums nicht mit den Maxwellgleichungen übereinstimmt - Pech für die Maxwellgleichungen. Falls die Beobachtungen ihr widersprechen - nun ja, diese Experimentatoren bauen manchmal Mist. -- Aber wenn Ihre Theorie nicht mit dem zweiten Hauptsatz der Thermodynamik übereinstimmt, dann kann ich Ihnen keine Hoffnung machen; ihr bleibt nichts übrig als in tiefster Schande aufzugeben.

ABUSE OF ENTROPY

"The tendency of institutions to become larger, more complex, and more centralized is the same tendency we see with various forms of technology. The reason for this can be found in the operation of the Entropy Law"

"While the Eastern religions have understood the value of minimizing energy flow and lessening the accumulation of disorder, it is the Western religions that have understood the linear nature of history, which is the other important factor in synthesizing a new religious doctrine in line with the requirements of the Entropy Law"

Rifkin and T. Howard, Entropy, A New World View (Granada Publ., London, 1985).

"Yet our personal lives also obey the Entropy Law. We go from birth to death". "The Second Law states unequivocally that the entropy of open [sic] systems must increase. Since we are all open systems, this means that all of us are doomed to die"

J.E. Lovelock, Gaia, A New Look at Life on Earth (OUP, 1987).

"Since biological information resides in biological systems and has a physical interpretation, it must be subject to the consequences of the second law"

B.H. Weber et al. (Herausg.), Entropy, Information, and Evolution (MIT Press, Cambridge, Mass., 1988), p. 177.

… and finally … from the Vatican

Pope XII: (Pontifical Academy of Sciences, 1952)

….The Second thermodynamic Law by Rudolph Clausius on Entropy increase gives us certainty that spontaneous, *natural processes* are always associated with a certain loss of free exploitable energy, which implies that they cease to exist in a closed materialistic, macroscopic system on the macroscopic level. This deplorable necessity provides a demonstrative testimony to the existence of a higher being [i.e. God]…..

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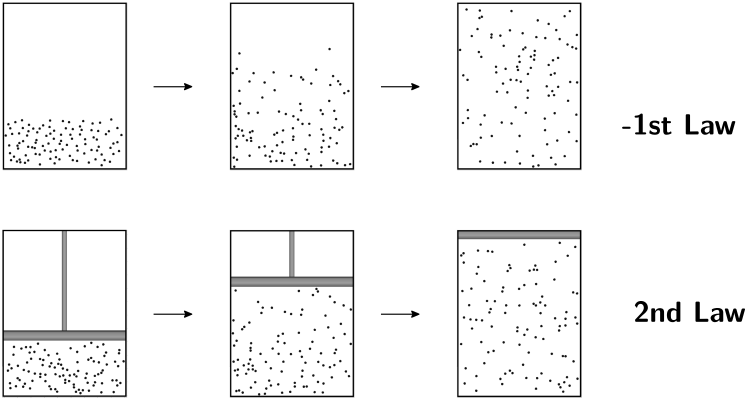
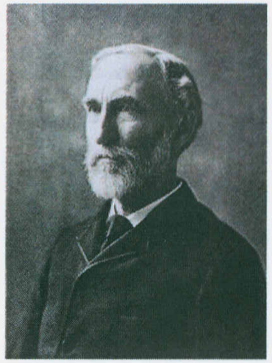
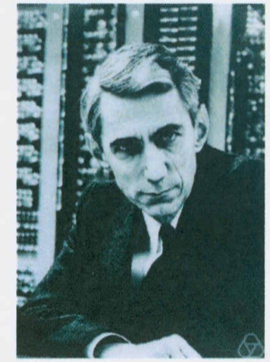
MINUS FIRST LAW vs. SECOND LAW





J. W. Gibbs

L. Boltzmann



C. E. Shannon

$$H_G = \int W_N \ln W_N \, d\Gamma_N \qquad H_B = N \int w_1 \ln w_1 \, d\Gamma_1$$

$$S_S = - \sum_i p_i \log_2 p_i$$

$$S_G = k_B \ln \Omega_G \qquad S_B = k_B \ln \left(\frac{\partial \Omega_G}{\partial E} \right) \delta E$$

Renyi

Relative-

Kullback-Leibler

v. NEUMANN

KOLMOGOROV-SINAI

CONDITIONAL

CLAUSIUS

FISHER

Daroczy-Harvda-Charvat-Tsallis

WEHRL

Hartley-chaitin

+ 200

ETC.

Vol. 30 (1991) *REPORTS ON MATHEMATICAL PHYSICS* No. 1

THE MANY FACETS OF ENTROPY

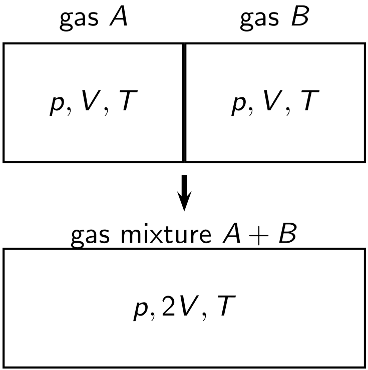
A. WEHRL

Institut für Theoretische Physik, Universität Wien, Baltzmanngane 5, A-1090, Wien, Austria

(*Received December 31, 1990*)

Several notions of entropy are discussed: classical entropies (Boltzmann, Gibbs, Shannon, quantum-mechanical entropy, skew entropy, among other notions as well as classical and quantum-mechanical dynamical entropies.

The Gibbs paradox in thermodynamics



Entropy change:

$$\Delta S := S_{A+B} - (S_A + S_B) = 2R \log 2$$

But is A is identical to B then $\Delta S = 0$

	Specific	Generic
Phase space	Γ	$\tilde{\Gamma} = \Gamma/\{\Pi\}$
phase space volume	dx	$d\tilde{x} = dx/N!$
partition function	$Z = \int_\Gamma e^{-\beta H(x)} dx$	$\tilde{Z} = Z/N!$
expectations	$\langle A \rangle_s = \frac{1}{Z} \int_\Gamma A e^{-\beta H} dx$	$\langle A \rangle_g = \frac{1}{\tilde{Z}} \int_\Gamma A e^{-\beta H} d\tilde{x}$
Entropy	$S = \frac{\partial}{\partial T}(kT \log Z)$	$\tilde{S} = \frac{\partial}{\partial T}(kT \log \tilde{Z}$

Only difference between specific and generic view in canonical ensemble is in the entropy

$$\tilde{S} = S - \log N! \approx S - N \log N - N$$

(But since N is constant in the canonical ensemble, this term can be absorbed in in the arbitrary additive constant.)
There are no empirical differences between the specific and generic viewpoints with a fixed N.
But Gibbs prefers generic viewpoint.

for an ideal gas one gets (ignoring terms depending only on T

$$S = \frac{3}{2} kN \log V \quad \text{not extensive}$$

$$\tilde{S} = \frac{3}{2} k \log V/N \quad \text{extensive}$$

For the entropy of mixing in the specific point of view

$$\begin{aligned} \Delta S &= S(2V, 2N) - 2S(V, N) = 3kN \log 2 && \text{same gases} \\ \Delta S &= 3kN \log 2 && \text{different gases} \end{aligned}$$

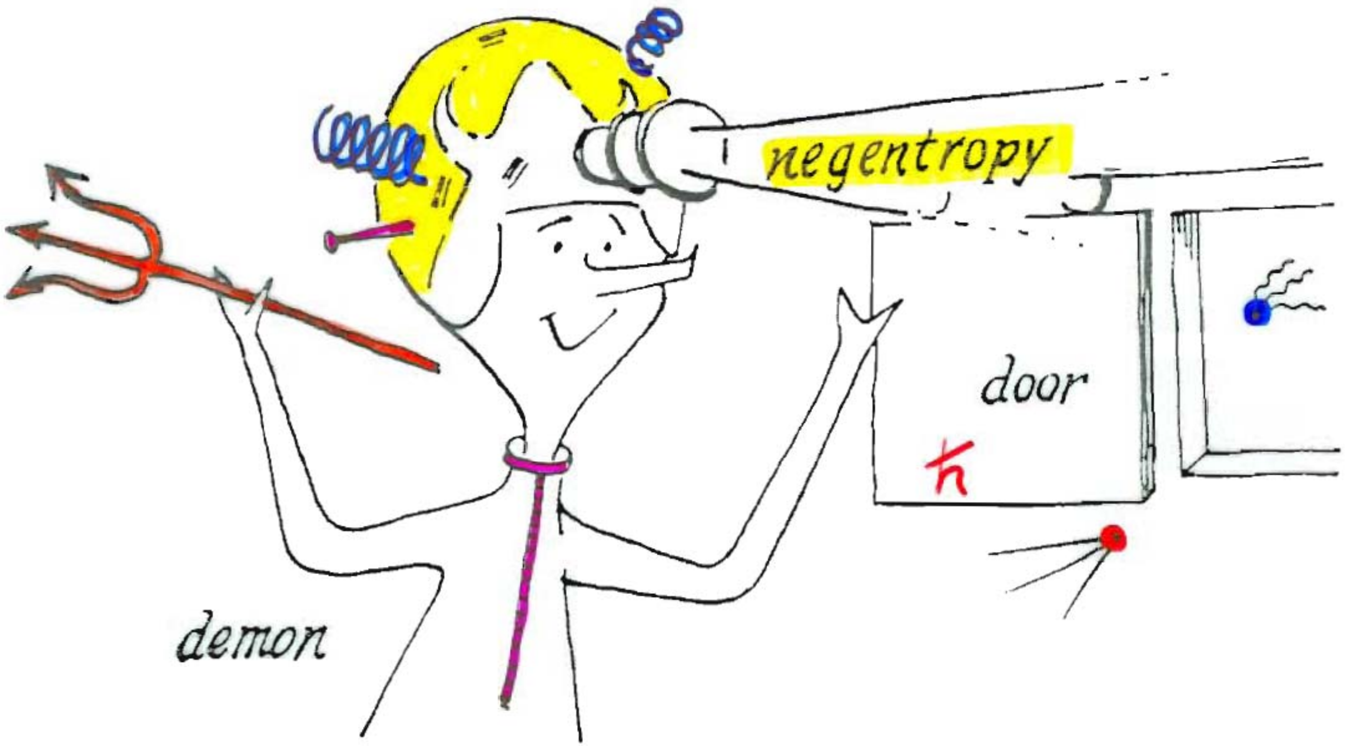
In generic viewpoint

$$\begin{aligned} \Delta S &= 0 \\ \Delta S &= 3kN \log 2 \end{aligned}$$

Hence, in the generic viewpoint we reproduce the Gibbs paradox of TD!

Quantum Demon ?

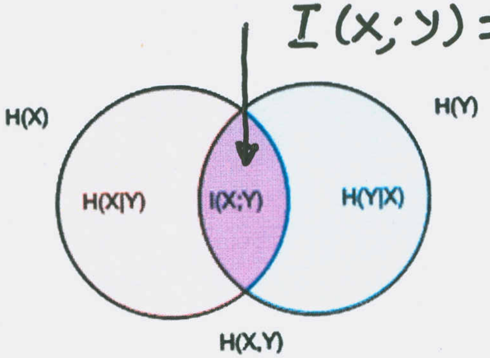
A measurement → Increase information → Reduction of entropy



Source: H.S. Leff, *Maxwell's Demon* (Adam Hilger, Bristol, 1990)

Conditional Entropy

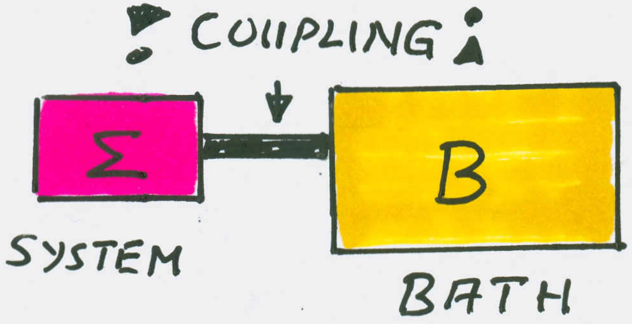
$$I(x;y) = H(x,y) - H(x|y) - H(y|x)$$



$$H(y|x) = -\sum_{x,y} p(x,y)\ln p(x,y) - \left(-\sum_{x} p(x)\ln p(x)\right) = -\sum_{x,y} p(x,y)\ln p(y|x) \geq 0$$

Quantum Conditional Entropy

von NEUMANN: $S_{vN}(\varrho_\Sigma) = -\mathrm{Tr}\,\varrho_\Sigma \ln \varrho_\Sigma$



$$S_\Sigma = S_{vN}\left(\varrho^{can}_{\Sigma\times B}\right) - S_{vN}\left(\varrho^{can}_{B}\right)$$

can. thermod. entropy

quantum cond. entropy

$$\overset{?!}{=} S_{vN}\left(\varrho^{can}_{\Sigma\times B}\right) - S_{vN}\left(\varrho_B = \mathrm{Tr}_\Sigma\, \varrho^{can}_{\Sigma\times B}\right)$$

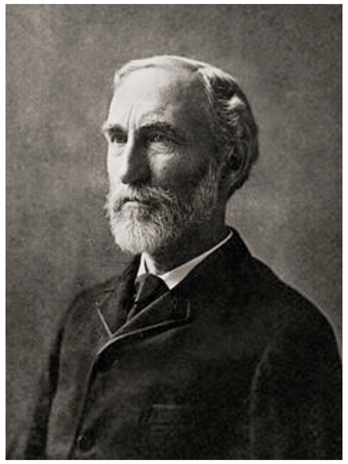
$\uparrow \neq \varrho_B^{can}$

GIBBS, JOSIAH WILLARD.

Elementary principles in statistical mechanics

Scribner's sons

New York 1902



CHAPTER VIII.

ON CERTAIN IMPORTANT FUNCTIONS OF THE ENERGIES OF A SYSTEM.

IN order to consider more particularly the distribution of a canonical ensemble in energy, and for other purposes, it will be convenient to use the following definitions and notations.

Let us denote by V the extension-in-phase below a certain limit of energy which we shall call ϵ. That is, let

$$V = \int \ldots \int dp_1 \ldots dq_n, \qquad (265)$$

the integration being extended (with constant values of the external coördinates) over all phases for which the energy is less than the limit ϵ. We shall suppose that the value of this integral is not infinite, except for an infinite value of the limiting energy. This will not exclude any kind of system to

CHAPTER XIV.

DISCUSSION OF THERMODYNAMIC ANALOGIES.

IF we wish to find in rational mechanics an *a priori* foundation for the principles of thermodynamics, we must seek mechanical definitions of temperature and entropy. The quantities thus defined must satisfy (under conditions and with limitations which again must be specified in the language of mechanics) the differential equation

$$d\epsilon = T\,d\eta - A_1\,da_1 - A_2\,da_2 - \text{etc.}, \qquad (482)$$

where ϵ, T, and η denote the energy, temperature, and entropy of the system considered, and $A_1\,da_1$, etc., the mechanical work (in the narrower sense in which the term is used in thermodynamics, *i. e.*, with exclusion of thermal action) done upon external bodies.

The quantity in the equation which corresponds to entropy is log V, the quantity V being defined as the extension-in-phase within which the energy is less than a certain limiting value (ϵ).

Entropy in Stat. Mech.

$$S = k_\mathrm{B} \ln \Omega(E, V, \ldots)$$

QM: $\Omega_\mathrm{G}(E, V, \ldots) = \sum_{0 \le E_i \le E} 1$

classical

Gibbs: $\Omega_\mathrm{G} = \left(\frac{1}{N!\, h^{\mathrm{DOF}}}\right) \int \mathrm{d}\Gamma\, \Theta\left(E - H(\underline{q}, \underline{p}; V, \ldots)\right)$

Boltzmann: $\Omega_\mathrm{B} = \epsilon_0 \frac{\partial\, \Omega_\mathrm{G}}{\partial E} \propto \int \mathrm{d}\Gamma\, \delta\left(E - H(\underline{q}, \underline{p}; V, \ldots)\right)$

density of states

A bit of thermodynamics

$$\beta = \frac{1}{k_\mathrm{B} T}$$

$$\begin{tikzcd}
 & \boxed{\text{density of states } \rho} & \\
 & \boxed{\text{canonical partition function } \mathcal{Z}} \arrow[u, "\mathcal{Z} = \int \mathrm{d}E \rho(E) \mathrm{e}^{-\beta E}"'] \arrow[dl, "U = -\frac{\partial \ln \mathcal{Z}}{\partial \beta}"'] \arrow[dr, "S = -\frac{\partial F}{\partial T} = -\frac{\partial k_\mathrm{B} T \ln \mathcal{Z}}{\partial T}"] & \\
\boxed{\text{internal energy } U} \arrow[dr, "C = \frac{\partial U}{\partial T}"'] & & \boxed{\text{entropy } S} \arrow[dl, "C = T \frac{\partial S}{\partial T}"] \\
 & \boxed{\text{specific heat } C} &
\end{tikzcd}$$

Thermodynamic Temperature

$$\delta Q^{\mathrm{rev}} = T\, dS \leftarrow \text{thermodynamic entropy}$$

$$S = S(E, V, N_1, N_2, ...; M, P, ...)$$

$S(E, ...)$: (continuous) & differentiable and
monotonic function of the internal energy E

$$\left(\frac{\partial S}{\partial E}\right)_{...} = \frac{1}{T}$$

$$E = E_{\mathrm{I}} + E_{\mathrm{II}}$$

$$\Omega_{\mathrm{I+II}}(E) = \int dE_{\mathrm{I}}\, \Omega'_{\mathrm{I}}(E_{\mathrm{I}})\, \Omega_{\mathrm{II}}(E - E_{\mathrm{I}})$$

$$\ln \Omega_{\mathrm{I+II}}(E) \neq \ln \Omega_{\mathrm{I}}(E_{\mathrm{I}}) + \ln \Omega_{\mathrm{II}}(E_{\mathrm{II}})$$

$$\omega_{\mathrm{I+II}}(E) = \int dE_{\mathrm{I}}\, \omega_{\mathrm{I}}(E_{\mathrm{I}})\, \omega_{\mathrm{II}}(E - E_{\mathrm{I}})$$

$$\ln \omega_{\mathrm{I+II}}(E) \neq \ln \omega_{\mathrm{I}}(E_{\mathrm{I}}) + \ln \omega_{\mathrm{II}}(E_{\mathrm{II}})$$

Not Additive !

canonical:

$$Z = \int_{E_0}^{\infty} e^{-\beta E} \omega(E) dE$$

$$Z_{\mathrm{I+II}}(T) = Z_{\mathrm{I}}(T) Z_{\mathrm{II}}(T)$$

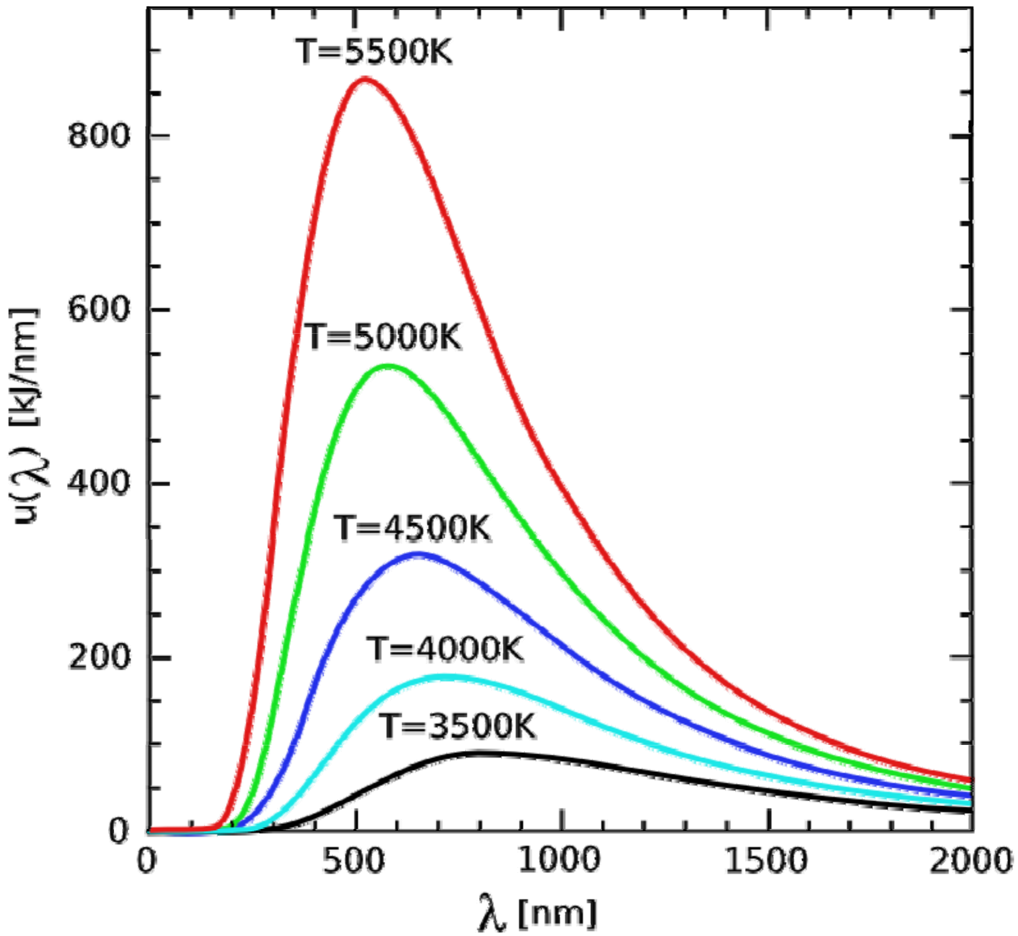
The highest temperature you can see

Lightning:

30 000 °C

Black body radiation

Planck's law [1901]: $u(\lambda, T) = \frac{8\pi hc}{\lambda^5} \frac{1}{\exp(\frac{hc}{\lambda k_B T}) - 1}$



$u(\lambda, T)$: spectral energy density

λ : wavelength

h : Planck constant

c : speed of light

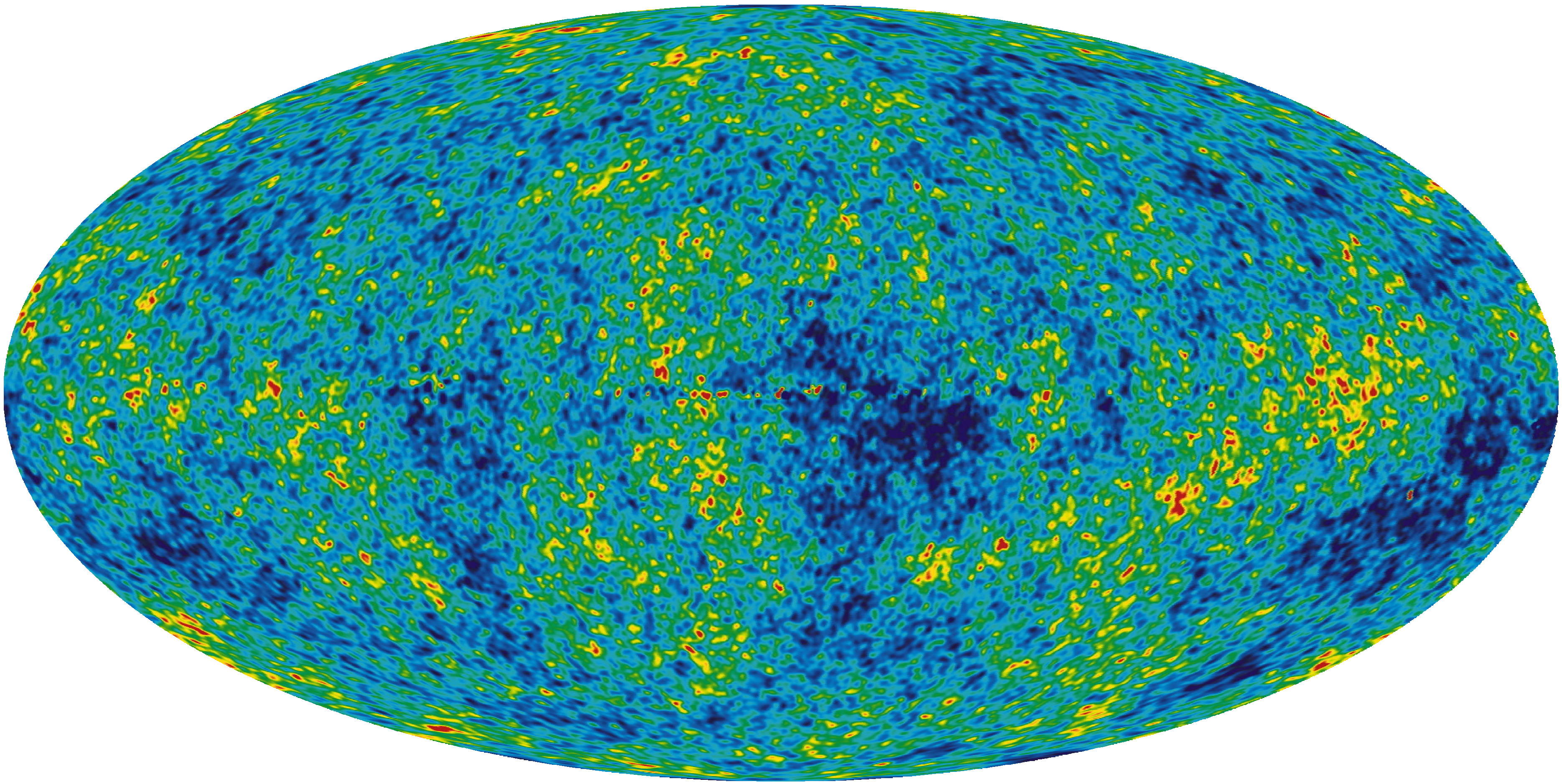
k_B : Boltzmann constant

Stefan – Boltzmann law:

$$E \propto T^4$$

Thermometer !

Cosmic background temperature



T = 2.725 ± …. K

Entropy in Stat. Mech.

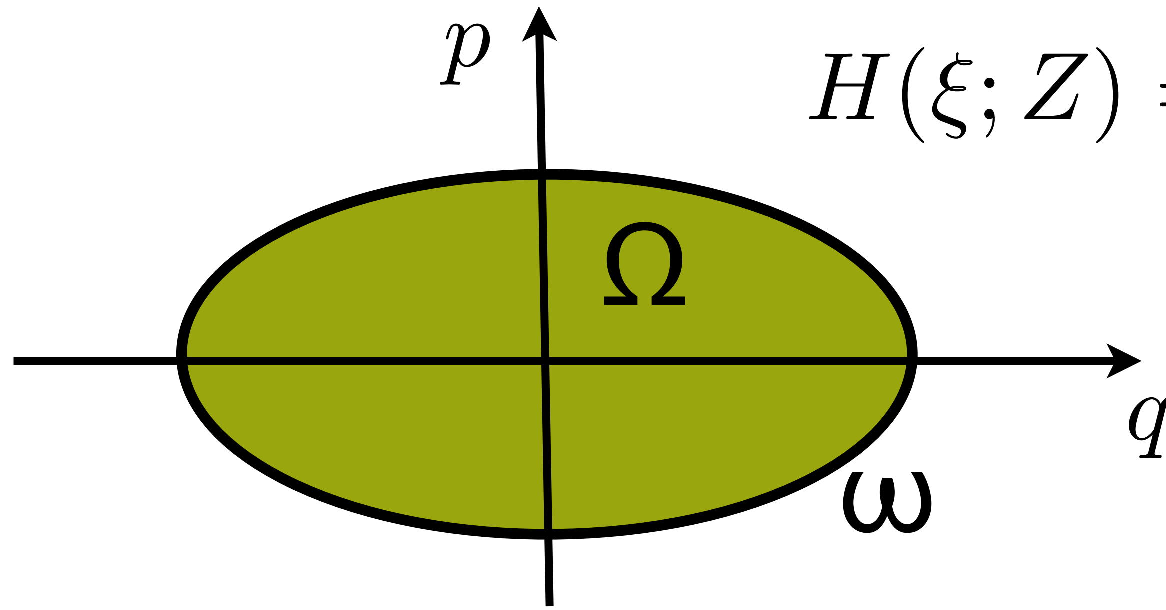
$$S = k_{\mathrm{B}} \ln \Omega(E, V, \ldots)$$

Gibbs: $\Omega_{\mathrm{G}} = \left(\frac{1}{N!\, h^{\mathrm{DOF}}}\right) \int \mathrm{d}\Gamma\, \Theta\left(E - H(\underline{q}, \underline{p}; V, \ldots)\right)$

Boltzmann: $\Omega_{\mathrm{B}} = \epsilon_0 \frac{\partial\, \Omega_{\mathrm{G}}}{\partial E} \propto \int \mathrm{d}\Gamma\, \delta\left(E - H(\underline{q}, \underline{p}; V, \ldots)\right)$

density of states

Microcanonical thermostatistics



$$H(\xi; Z) = E$$

D-Operator

$$\rho(\boldsymbol{\xi}|E, Z) = \frac{\delta(E - H)}{\omega}$$

DoS

$$\omega(E, Z) = \mathrm{Tr}[\delta(E - H)] \geq 0$$

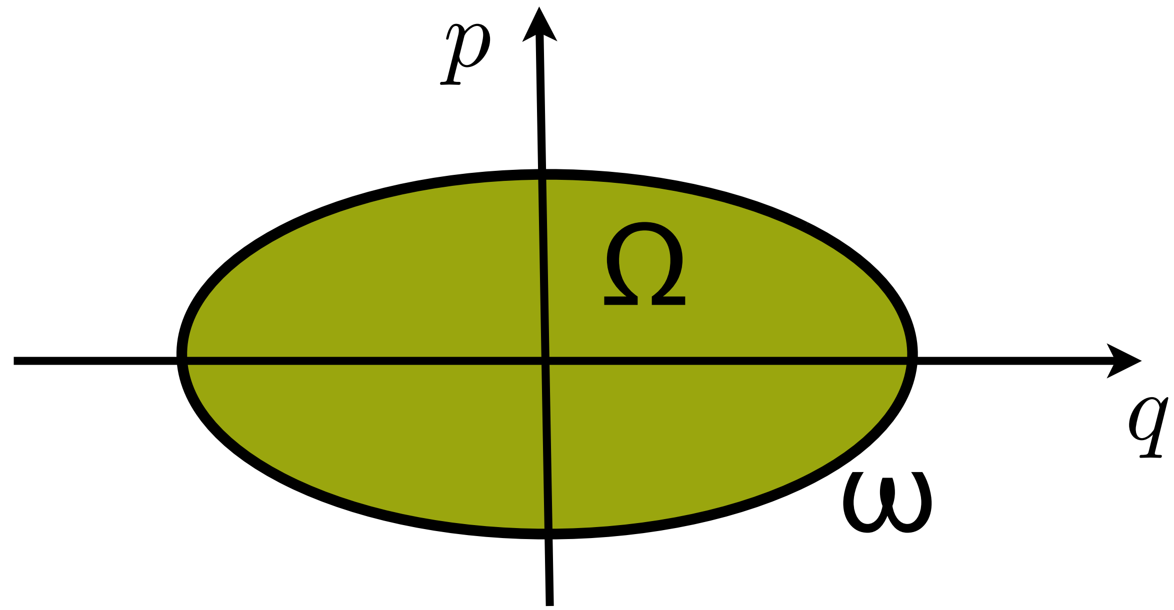
$$\Omega(E, Z) = \mathrm{Tr}[\Theta(E - H)]$$

IntDoS

Thermodynamic Entropy ?

$S_{\mathrm{B}}(E) = \ln(\epsilon\, \omega)$ Boltzmann (?)	*vs.*	$S_{\mathrm{G}}(E) = \ln \Omega$ Gibbs (1902), Hertz (1910)

Boltzmann *vs.* Gibbs



$$S_{\mathrm{B}}(E) = \ln\left(\epsilon\, \omega\right) \qquad\qquad S_{\mathrm{G}}(E) = \ln \Omega$$

$$T(E, Z) \equiv \left(\frac{\partial S}{\partial E}\right)^{-1}$$

$$T_{\mathrm{B}}(E) = \frac{\omega}{\nu} \ \gtrless 0 \qquad\qquad T_{\mathrm{G}}(E) = \frac{\Omega}{\omega} \ \geq 0$$

$$\nu(E, Z) = \partial\omega/\partial E,$$

? Negative Temperature ?

Spin system: $|\vec{S}| = 1/2; \quad \vec{\mu} = \gamma \vec{S}; \quad H = -\sum \vec{\mu}_i \cdot \vec{B}$

$\vec{S} \parallel \vec{B} \Rightarrow$ Two-State-System: $\epsilon_g = -\frac{1}{2}\gamma B < \epsilon_e = +\frac{1}{2}\gamma B = \mu B$

$N = n_g + n_e \;\; \& E = \mu B(n_e - n_g)$, typically $E < 0$

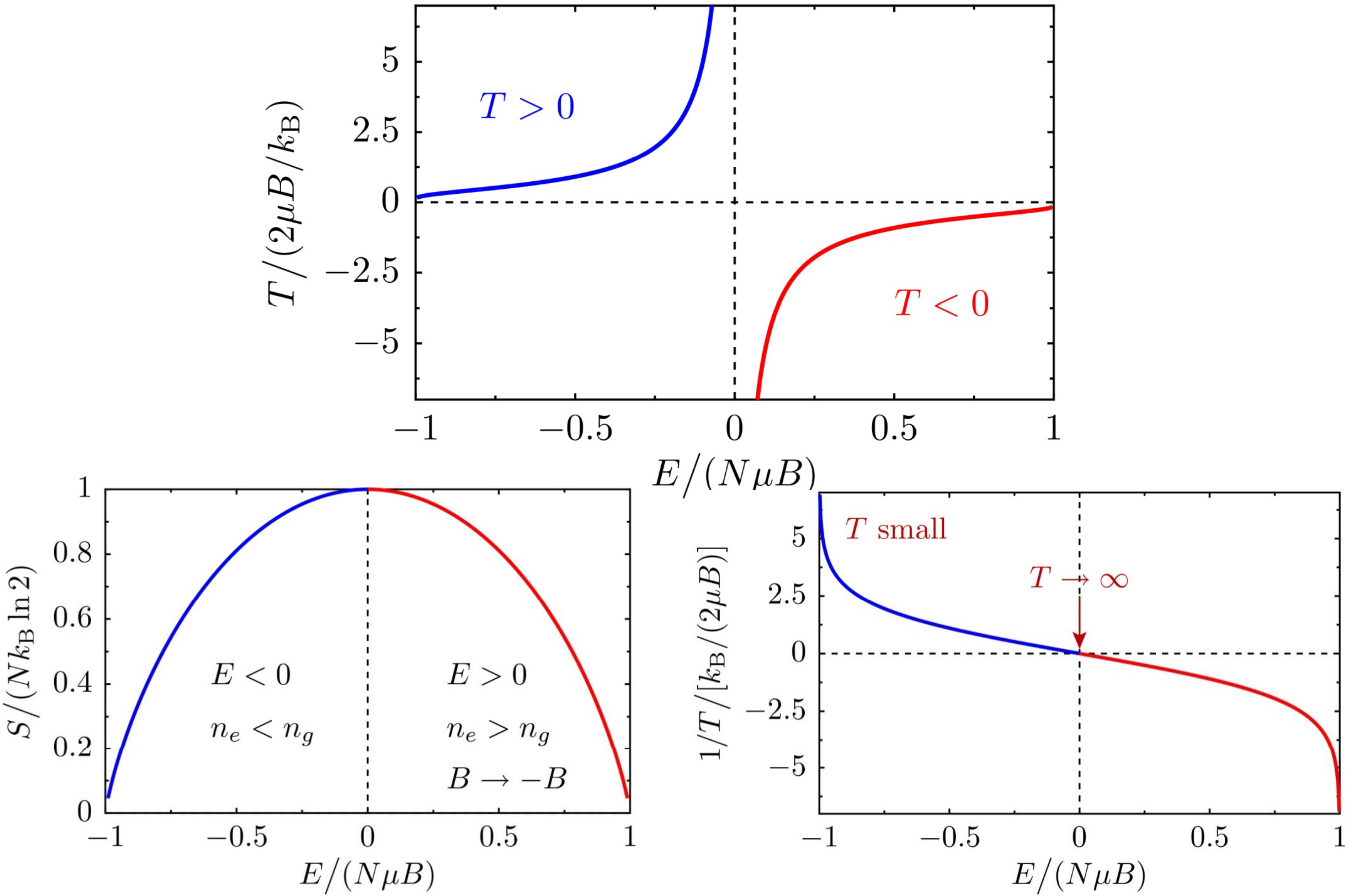
$$\omega = \frac{N!}{n_g! n_e!} \Rightarrow S_B = k_B \ln \omega$$

$$\Rightarrow n_g = \frac{1}{2}\left(N - \frac{E}{\mu B}\right)$$

$$\Rightarrow n_e = \frac{1}{2}\left(N + \frac{E}{\mu B}\right)$$

$$\Rightarrow \frac{1}{T_B} = \frac{\partial S_B}{\partial E}$$

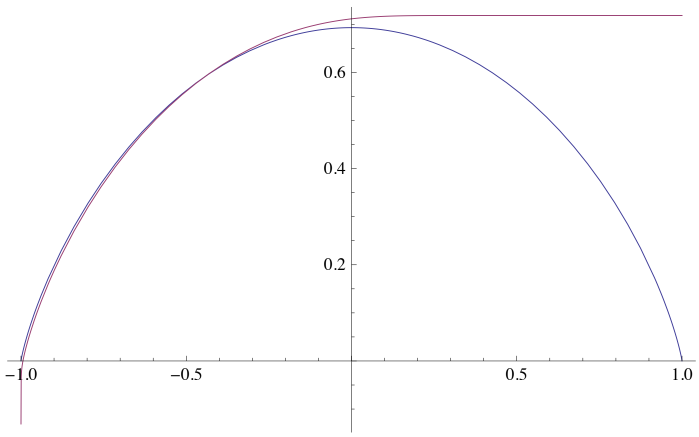
Negative (Spin)-Temperature!



```
In[1]:= SΩ[x_, n_, μ_, B_] :=
         n Log[2] - n / 2 (1 + x / (μ B n)) Log[1 + x / (μ B n)] - n / 2 (1 - x / (μ B n)) Log[1 - x / (μ B n)]
        W[x_, n_, μ_, B_] := Exp[SΩ[x, n, μ, B]]
        Ω[x_, n_, μ_, B_] := Exp[SΩ[x, n, μ, B]] / (2 μ B)
        Ωe[x_, n_, μ_, B_] := Derivative[1, 0, 0, 0][Ω][x, n, μ, B]
        ΩB[x_, n_, μ_, B_] := Derivative[0, 0, 0, B][Ω][x, n, μ, B]
        Φ[x_, n_, μ_, B_] := NIntegrate[Ω[y, n, μ, B], {y, -n μ B, x}]
        ΦB[x_, n_, μ_, B_] := NIntegrate[ΩB[y, n, μ, B], {y, -n μ B, x}]
        S[x_, n_, μ_, B_] := Log[Φ[x, n, μ, B]]
        T[x_, n_, μ_, B_] := Φ[x, n, μ, B] / Ω[x, n, μ, B]
        TΩ[x_, n_, μ_, B_] := Ω[x, n, μ, B] / Ωe[x, n, μ, B]
        MΩ[x_, n_, μ_, B_] := ΩB[x, n, μ, B] / Ωe[x, n, μ, B]
        M[x_, n_, μ_, B_] := -x / B

In[22]:= n = 10^2;
         m = 10^8;
         Plot[{SΩ[e n, n, 1, 1] / n, S[e n, n, 1, 1] / n}, {e, -1, 1}]
         Plot[{SΩ[e m, m, 1, 1] / m, S[e m, m, 1, 1] / m}, {e, -1, 1}]
         Plot[{TΩ[e n, n, 1, 1], T[e n, n, 1, 1]}, {e, -1, 1}, PlotRange → {-100, 100}]
         Plot[{TΩ[e m, m, 1, 1], T[e m, m, 1, 1]}, {e, -1, 1}, PlotRange → {-100, 100}]
         Plot[{MΩ[e n, n, 1, 1] / n, M[e n, n, 1, 1] / n}, {e, -1, 1}]
         Plot[{MΩ[e m, m, 1, 1] / m, M[e m, m, 1, 1] / m}, {e, -1, 1}]
         Clear[n, m]
```

Out[24]=

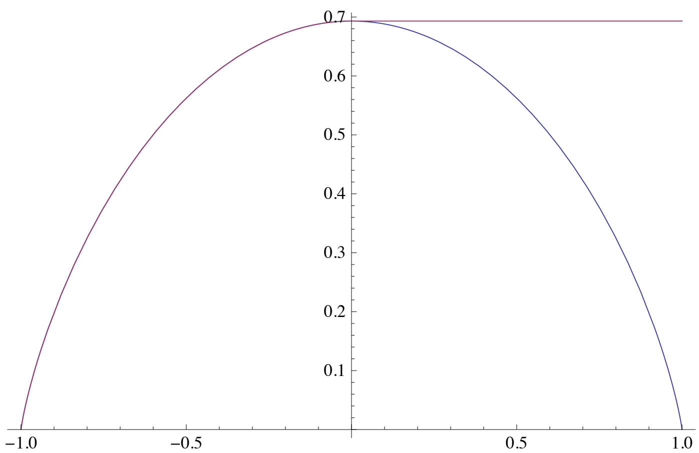


Purple: S_Phi /N
Blue: S_Omega/N

N=100

x-axis in all graphs is E/(2\mu N)

Out[25]=

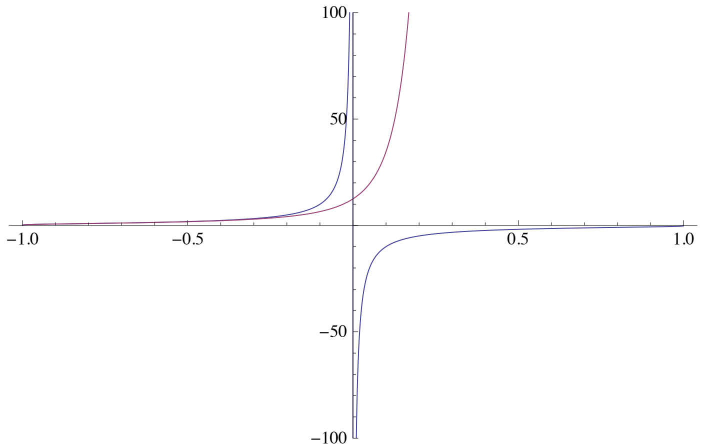


Purple: S_Phi /N
Blue: S_Omega/N

N=10^8

Limit Value = Log 2

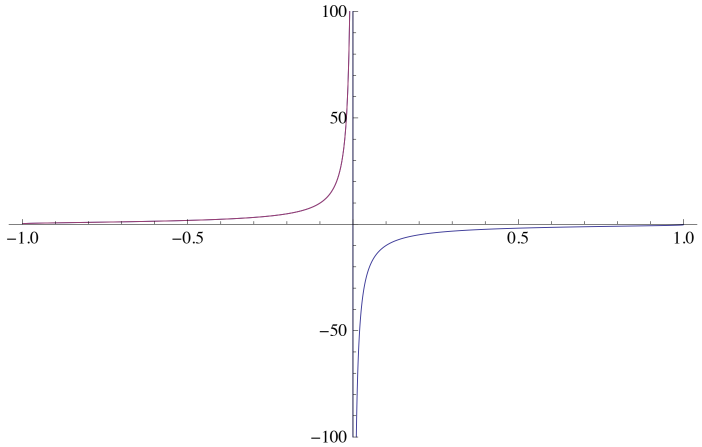
Out[26]=



Purple: T_Phi
Blue: T_Omega

N=100

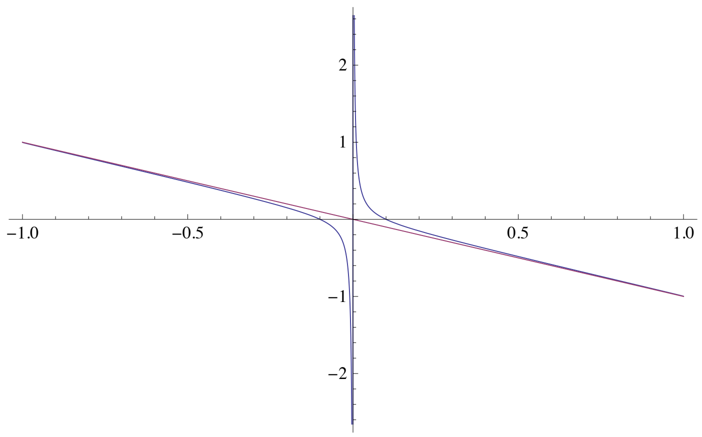
Out[27]=



Purple: T_Phi
Blue: T_Omega

N=10^8

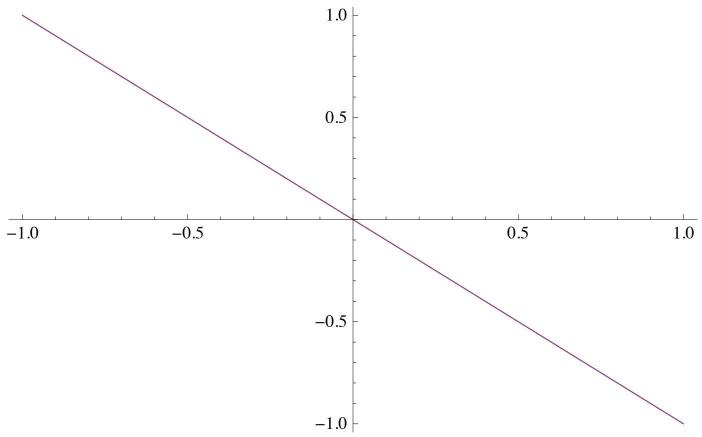
Out[28]=



Purple: M_Phi
Blue: M_Omega

N=100

Out[29]=



Purple: M_Phi
Blue: M_Omega

N=10^8

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Thermodynamic laws in isolated systems

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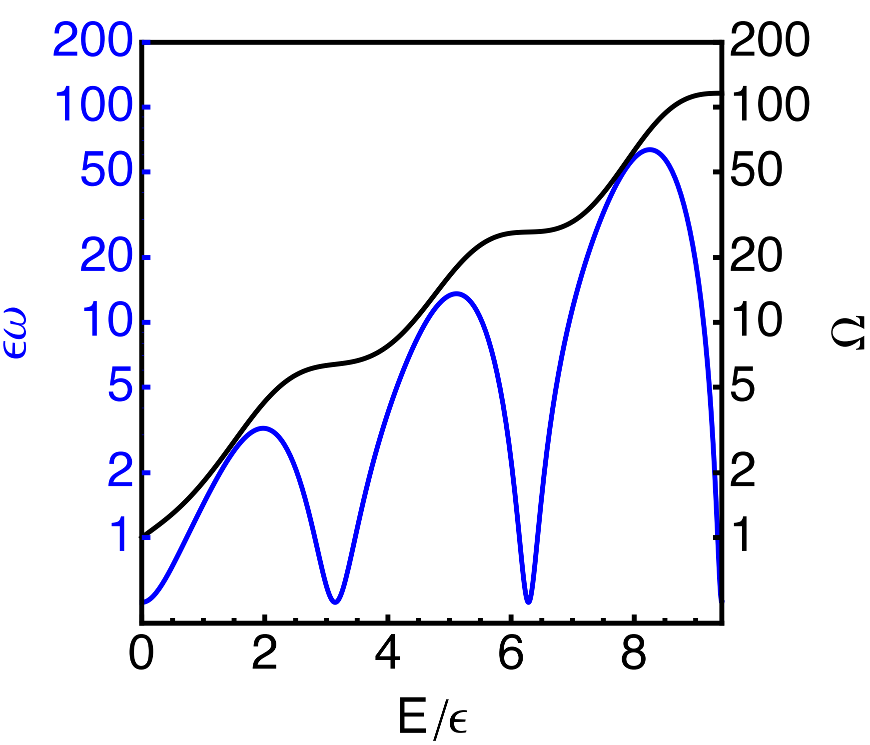
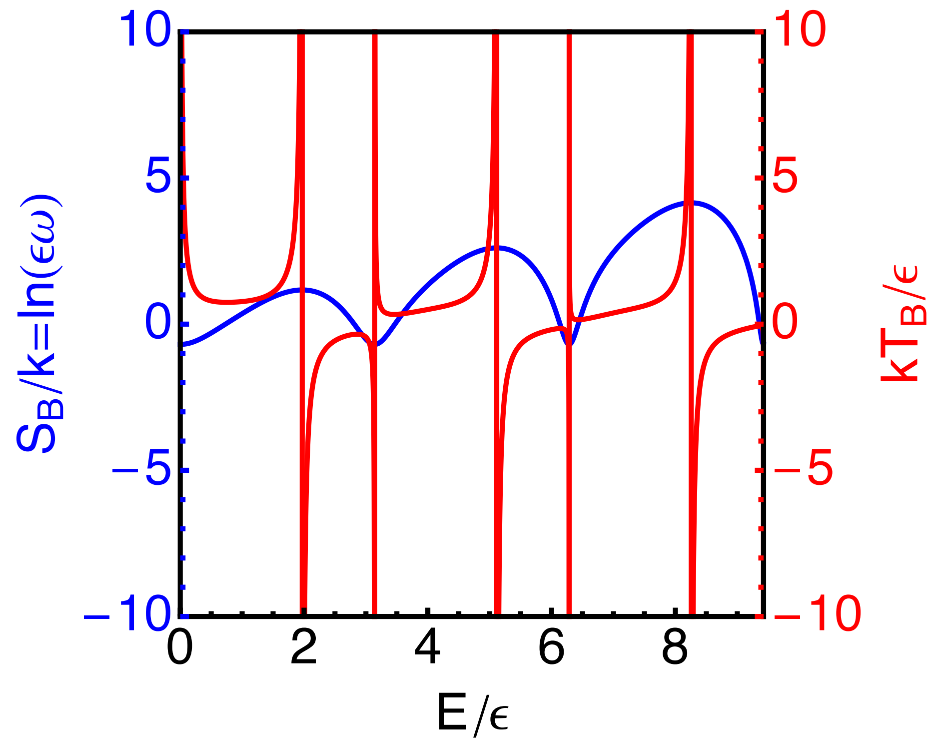
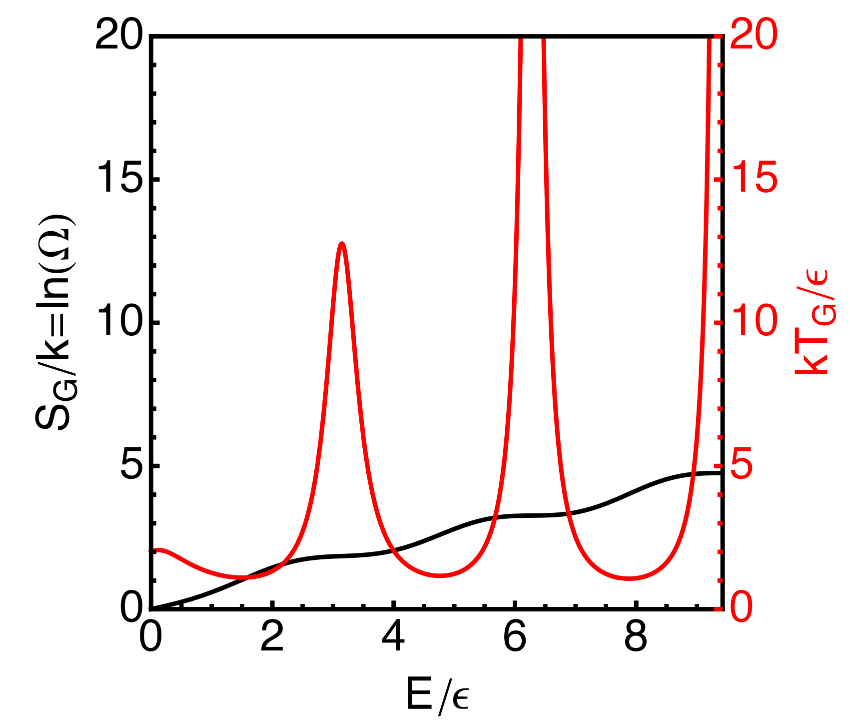
**** 23 pages ****

‘Non-uniqueness’ of temperature

$$\Omega(E) = \exp\left[\frac{E}{2\epsilon} - \frac{1}{4}\sin\left(\frac{2E}{\epsilon}\right)\right] + \frac{E}{2\epsilon},$$







Temperature does NOT determine direction heat flow.

Energy is primary control parameter of MCE.

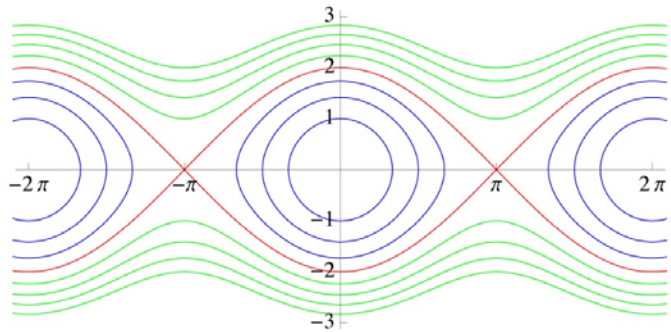


FIG. 1. A pendulum moves in phase space (θ, p) along lines of constant energy, $H(\theta, p) = E$. Blue: finite trajectories (oscillations) for $E < 2$. Green: infinite trajectories (rotation) for $E > 2$. Red: the critical contour, $E = 2$, separating finite and infinite trajectories.

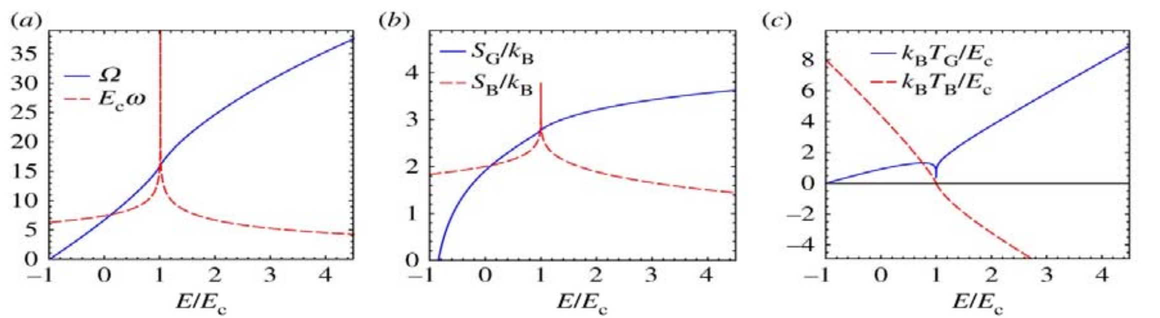
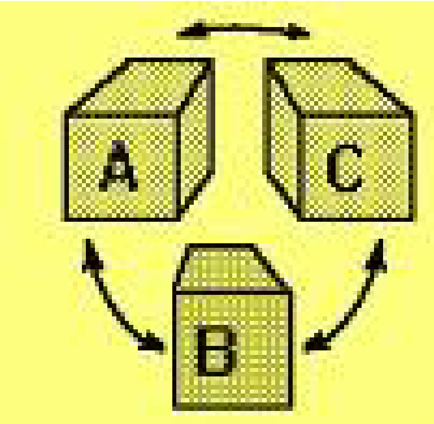


Figure 1. Microcanonical thermostatistics of the pendulum with Hamiltonian (2.10). (*a*) The integrated DoS Ω (blue) grows monotonically while the DoS ω (red dashed) exhibits a singular peak at the critical energy $E_c = mgL$, indicating a change in the phase-space topology. (*b*) The Gibbs entropy S_G (blue) increases monotonically, whereas the Boltzmann entropy S_B (red dashed) becomes singular at E_c and decays for $E > E_c$. (*c*) The Gibbs temperature T_G (blue) approaches asymptotically the caloric equation of state of the ideal one-particle gas, whereas the Boltzmann temperature T_B (red dashed) becomes negative for $E > E_c$.

Zeroth Law



Transitivity !

$$
\begin{aligned}
\text{A in equilibrium with B:} \quad & f_{\mathrm{AB}}(p_{\mathrm{A}}, V_{\mathrm{A}}; p_{\mathrm{B}}, V_{\mathrm{B}}, \ldots) = 0 \\
\text{B in equilibrium with C:} \quad & f_{\mathrm{BC}}(p_{\mathrm{B}}, V_{\mathrm{B}}; p_{\mathrm{C}}, V_{\mathrm{C}}, \ldots) = 0 \\
\Rightarrow \text{A in equilibrium with C} \Leftrightarrow & f_{\mathrm{AC}}(p_{\mathrm{A}}, V_{\mathrm{A}}; p_{\mathrm{C}}, V_{\mathrm{C}}, \ldots) = 0
\end{aligned}
$$

Allows the formal introduction of a temperature:

$$
T = T_{\mathrm{A}}(p_{\mathrm{A}}, V_{\mathrm{A}}; \ldots) = T_{\mathrm{B}}(p_{\mathrm{B}}, V_{\mathrm{B}}; \ldots) = T_{\mathrm{C}}(p_{\mathrm{C}}, V_{\mathrm{C}}; \ldots)
$$

Thermal equilibrium

before coupling

$$H_{\mathcal{A}} = E_{\mathcal{A}} \qquad\qquad H_{\mathcal{B}} = E_{\mathcal{B}}$$

$\mathcal{A}$ $\qquad$ $\mathcal{B}$

$$T_{\mathcal{A}}(E_{\mathcal{A}}) \qquad\qquad T_{\mathcal{B}}(E_{\mathcal{B}})$$

after coupling

$$H = H_{\mathcal{A}} + H_{\mathcal{B}} = E_{\mathcal{A}} + E_{\mathcal{B}} = E$$

$\mathcal{A}$ $\qquad$ $T(E)$ $\qquad$ $\mathcal{B}$

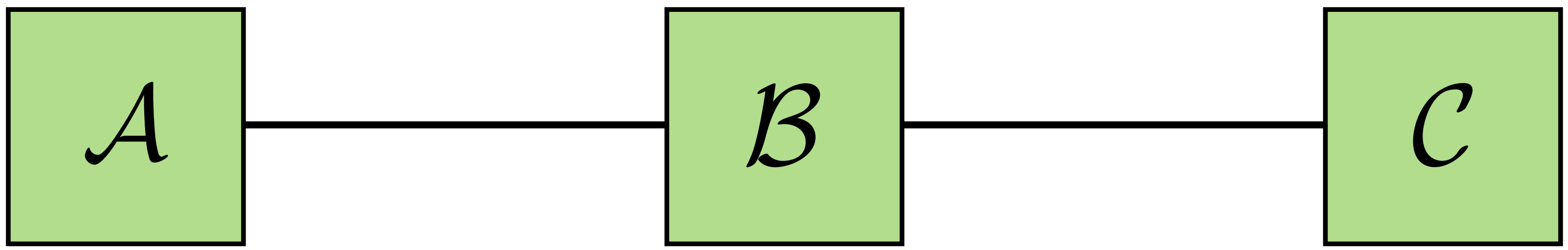
$$\langle T_{\mathcal{A}}(E_{\mathcal{A}})\rangle_E \qquad\qquad \langle T_{\mathcal{B}}(E_{\mathcal{B}})\rangle_E$$

$$\langle T_i(E_i)\rangle_E = \int_0^\infty dE_i\ T_i(E_i)\,\pi_i(E_i|E)$$

$$\pi_{\mathcal{A}}(E_{\mathcal{A}}|E) = \frac{\omega_{\mathcal{A}}(E_{\mathcal{A}})\,\omega_{\mathcal{B}}(E-E_{\mathcal{A}})}{\omega(E)}.$$

Zeroth law

$T(E)$



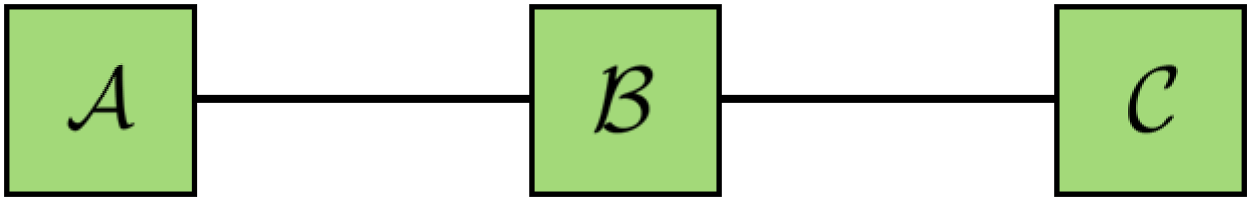
$\langle T_{\mathcal{A}}(E_{\mathcal{A}})\rangle_E$ $\langle T_{\mathcal{B}}(E_{\mathcal{B}})\rangle_E$ $\langle T_{\mathcal{C}}(E_{\mathcal{C}})\rangle_E$

$$\langle T_{\mathcal{A}}(E_{\mathcal{A}})\rangle_E = \langle T_{\mathcal{B}}(E_{\mathcal{B}})\rangle_E = \langle T_{\mathcal{C}}(E_{\mathcal{C}})\rangle_E$$

holds if $\langle T_i(E_i)\rangle_E \stackrel{!}{=} T(E)$

Zeroth law

$$T(E)$$



$$\langle T_{\mathcal{A}}(E_{\mathcal{A}})\rangle_E \qquad \langle T_{\mathcal{B}}(E_{\mathcal{B}})\rangle_E \qquad \langle T_{\mathcal{C}}(E_{\mathcal{C}})\rangle_E$$

$$\langle T_i(E_i)\rangle_E \stackrel{!}{=} T(E)$$

Boltzmann

$$\langle T_{\mathrm{B}\mathcal{A}}(E_{\mathcal{A}})\rangle_E \;=\; \int_0^E \mathrm{d}E_{\mathcal{A}} \frac{\omega_{\mathcal{A}}(E_{\mathcal{A}})\omega_{\mathcal{B}}(E-E_{\mathcal{A}})}{\omega(E)} \frac{\omega_{\mathcal{A}}(E_{\mathcal{A}})}{\nu_{\mathcal{A}}(E_{\mathcal{A}})} \;\neq\; T_{\mathrm{B}}(E)$$

satisfies instead $\left\langle \frac{1}{T_{\mathrm{B}\mathcal{A}}} \right\rangle_E = \left\langle \frac{1}{T_{\mathrm{B}\mathcal{B}}} \right\rangle_E = \frac{1}{T_{\mathrm{B}}(E)}$

Second law

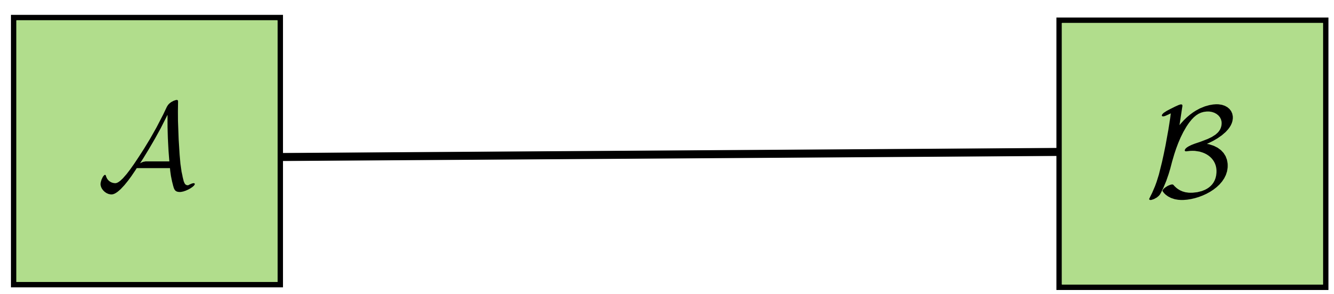
before
coupling

$$H_{\mathcal{A}} = E_{\mathcal{A}} \qquad\qquad H_{\mathcal{B}} = E_{\mathcal{B}}$$

$$S_{\mathcal{A}}(E_{\mathcal{A}}) \qquad\qquad S_{\mathcal{B}}(E_{\mathcal{B}})$$

after
coupling

$$H = H_{\mathcal{A}} + H_{\mathcal{B}} = E_{\mathcal{A}} + E_{\mathcal{B}} = E$$



$$S_{\mathcal{AB}}(E)$$

$$S_{\mathcal{AB}}(E_{\mathcal{A}} + E_{\mathcal{B}}) \geq S_{\mathcal{A}}(E_{\mathcal{A}}) + S_{\mathcal{B}}(E_{\mathcal{B}})$$

Second law

Gibbs

$$S_{\mathrm{G}}(E) = \ln \Omega$$

$$\begin{aligned}
&\Omega(E_{\mathcal{A}} + E_{\mathcal{B}}) \\
&= \int_0^{E_{\mathcal{A}}+E_{\mathcal{B}}} \mathrm{d}E' \, \Omega_{\mathcal{A}}(E') \omega_{\mathcal{B}}(E_{\mathcal{A}} + E_{\mathcal{B}} - E') \\
&= \int_0^{E_{\mathcal{A}}+E_{\mathcal{B}}} \mathrm{d}E' \int_0^{E'} \mathrm{d}E'' \omega_{\mathcal{A}}(E'') \omega_{\mathcal{B}}(E_{\mathcal{A}} + E_{\mathcal{B}} - E') \\
&\geq \int_{E_{\mathcal{A}}}^{E_{\mathcal{A}}+E_{\mathcal{B}}} \mathrm{d}E' \int_0^{E_{\mathcal{A}}} \mathrm{d}E'' \omega_{\mathcal{A}}(E'') \omega_{\mathcal{B}}(E_{\mathcal{A}} + E_{\mathcal{B}} - E') \\
&= \int_0^{E_{\mathcal{A}}} \mathrm{d}E'' \omega_{\mathcal{A}}(E'') \int_0^{E_{\mathcal{B}}} \mathrm{d}E''' \omega_{\mathcal{B}}(E''') \\
&= \Omega_{\mathcal{A}}(E_{\mathcal{A}}) \, \Omega_{\mathcal{B}}(E_{\mathcal{B}}).
\end{aligned}$$

$$\Rightarrow \quad S_{\mathrm{G}\,\mathcal{A}\mathcal{B}}(E_{\mathcal{A}} + E_{\mathcal{B}}) \geq S_{\mathrm{G}\,\mathcal{A}}(E_{\mathcal{A}}) + S_{\mathrm{G}\,\mathcal{B}}(E_{\mathcal{B}})$$

✓

Second law

Boltzmann $$S_{\mathrm{B}}(E) = \ln\left(\epsilon\,\omega\right)$$

$$\epsilon\omega(E_{\mathcal{A}} + E_{\mathcal{B}}) = \epsilon \int_0^{E_{\mathcal{A}}+E_{\mathcal{B}}} \mathrm{d}E'\omega_{\mathcal{A}}(E')\omega_{\mathcal{B}}(E_{\mathcal{A}} + E_{\mathcal{B}} - E')$$

$$\cancel{\geq} \quad \epsilon^2\omega_{\mathcal{A}}(E_{\mathcal{A}})\omega_{\mathcal{B}}(E_{\mathcal{B}})$$

First law

$$dE \;=\; \delta Q + \delta A \;=\; T\, dS - \sum_n p_n dZ_n$$

$$p_j = T \left(\frac{\partial S}{\partial Z_j} \right)_{E, Z_n \neq Z_j} \stackrel{!}{=} - \left\langle \frac{\partial H}{\partial Z_j} \right\rangle_E$$

Gibbs

$$T_{\mathrm{G}} \left(\frac{\partial S_{\mathrm{G}}}{\partial Z_j} \right) = \frac{1}{\omega} \frac{\partial}{\partial Z_j} \mathrm{Tr} \Big[\Theta(E - H) \Big] = -\frac{1}{\omega} \mathrm{Tr} \left[-\frac{\partial}{\partial Z_j} \Theta(E - H) \right]$$

$$= -\mathrm{Tr} \left[\left(\frac{\partial H}{\partial Z_j} \right) \frac{\delta(E - H)}{\omega} \right] = - \left\langle \frac{\partial H}{\partial Z_j} \right\rangle$$

see also Campisi, Physica A 2007

Entropy	$S(E)$	second law Eq. (38)	first law Eq. (37)	zeroth law Eq. (20)	equip artition equipartition
Gibbs	$\ln \Omega$	yes	yes	yes	yes
Penrose	$\ln \Omega + \ln(\Omega_\infty - \Omega) - \ln \Omega_\infty$	yes	yes	no	no
Complementary Gibbs	$\ln[\Omega_\infty - \Omega]$	yes	yes	no	no
Differential Boltzmann	$\ln[\Omega(E+\epsilon) - \Omega(E)]$	yes	no	no	no
Boltzmann	$\ln(\epsilon\omega)$	no	no	no	no

Hilbert, Hänggi & Dunkel, in preparation, 2014

Inconsistent thermostatistics
and
negative absolute temperatures

Jörn Dunkel and Stefan Hilbert,

nature physics 10: 67-72 (2014)

& ! SUPPL. -MATERIAL !

Example 1: Classical ideal gas

$$\Omega(E, V) = \alpha E^{dN/2} V^N, \qquad \alpha = \frac{(2\pi m)^{dN/2}}{N! h^d \Gamma(dN/2 + 1)}$$

$$S_{\mathrm{B}}(E, V, A) = k_{\mathrm{B}} \ln[\epsilon \omega(E)]$$

$$E = \left(\frac{dN}{2} - 1\right) k_{\mathrm{B}} T_{\mathrm{B}}$$

vs.

$$S_{\mathrm{G}}(E, V, A) = k_{\mathrm{B}} \ln[\Omega(E)]$$

$$E = \frac{dN}{2} k_{\mathrm{B}} T_{\mathrm{G}}$$

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vs.

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$$E = \frac{dN}{2} k_{\mathrm{B}} T_{\mathrm{G}}$$

Example 3: 1-dim 1-particle quantum gas

$$E_n = an^2/L^2, \qquad a = \hbar^2\pi^2/(2m), \qquad n = 1, 2, \ldots, \infty$$

$$\Omega = n = L\sqrt{E/a}$$

$$S_{\mathrm{B}}(E, V, A) = k_{\mathrm{B}} \ln[\epsilon\omega(E)]$$

$$k_{\mathrm{B}}T_{\mathrm{B}} = -2E < 0$$

$$p_{\mathrm{B}} \equiv T_{\mathrm{B}}\left(\frac{\partial S_{\mathrm{B}}}{\partial L}\right) = -\frac{2E}{L} \neq p$$

Dark energy ???

vs.

$$S_{\mathrm{G}}(E, V, A) = k_{\mathrm{B}} \ln[\Omega(E)]$$

$$k_{\mathrm{B}}T_{\mathrm{G}} = 2E, \qquad p_G \equiv T_{\mathrm{G}}\left(\frac{\partial S_{\mathrm{G}}}{\partial L}\right) = \frac{2E}{L}$$

$$p \equiv -\frac{\partial E}{\partial L} = \frac{2E}{L} = p_{\mathrm{G}}$$

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$$\cancel{p_\mathrm{B} \equiv T_\mathrm{B}\left(\frac{\partial S_\mathrm{B}}{\partial L}\right) = -\frac{2E}{L} \neq p}$$

~~*Dark energy ???*~~

vs.

$$S_\mathrm{G}(E, V, A) = k_\mathrm{B} \ln[\Omega(E)]$$

$$k_\mathrm{B} T_\mathrm{G} = 2E, \qquad p_G \equiv T_\mathrm{G}\left(\frac{\partial S_\mathrm{G}}{\partial L}\right) = \frac{2E}{L}$$

$$p \equiv -\frac{\partial E}{\partial L} = \frac{2E}{L} = p_\mathrm{G}$$

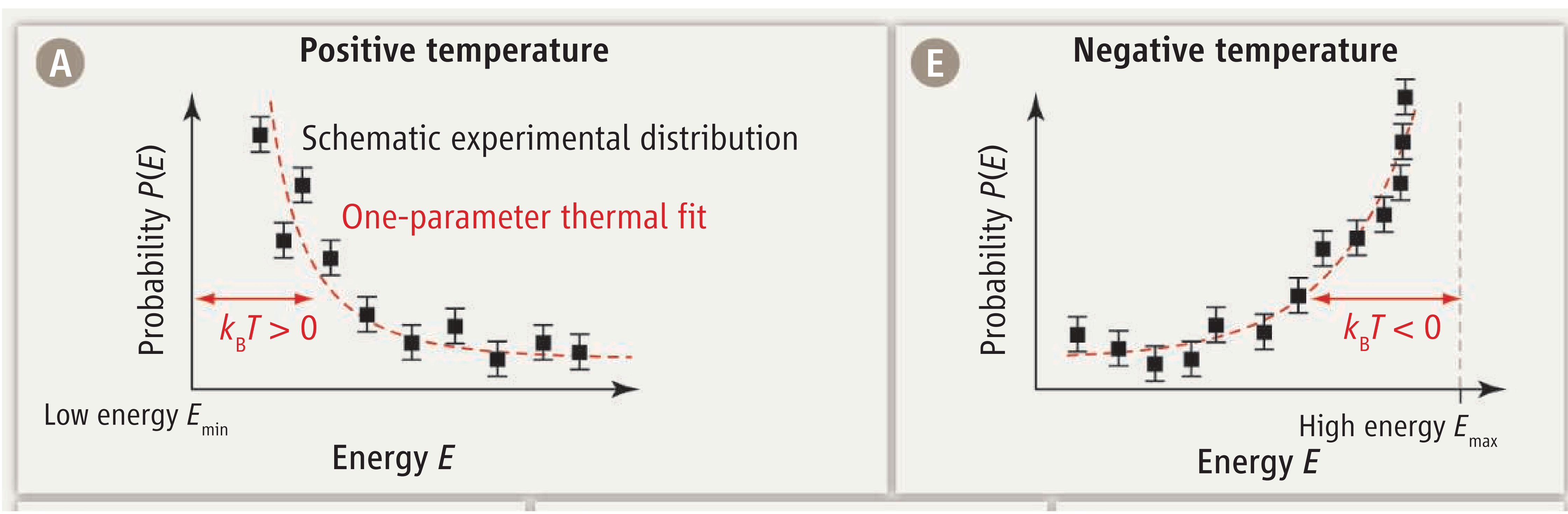
PERSPECTIVES 4 JANUARY 2013 VOL 339 SCIENCE

PHYSICS

Negative Temperatures?

Lincoln D. Carr

$$P_i \propto e^{-E_i/k_B T}$$



Population inversion of one-particle levels

Experimental evidence (?)

A Nuclear Spin System at Negative Temperature

E. M. Purcell and R. V. Pound
Department of Physics, Harvard University, Cambridge, Massachusetts
November 1, 1950

At field strengths allowing the system to be described by its net magnetic moment and angular momentum, a sufficiently rapid reversal of the direction of the magnetic field should result in a magnetization opposed to the new sense of the field. The reversal must occur in such a way that the time spent below a minimum effective field is so small compared to the period of the Larmor precession that the system cannot follow the change adiabatically. The experiments in zero field reported above[2] showed a zero field resonance at about 50 kc and therefore the following experiment was tried.

nuclear spin population inversion in LiF crystal due to rapid switching of MF

A system in a negative temperature state is not cold, but very hot, giving up energy to any system at positive temperature put into contact with it. It decays to a normal state through infinite temperature.

E. M. Purcell and R. V. Pound. A nuclear spin system at negative temperature. *Phys. Rev.*, 81(2):279–280, 1951.

EMP
Nobel 1952

SCIENCE VOL 339 4 JANUARY 2013

Negative Absolute Temperature for Motional Degrees of Freedom

S. Braun,[1,2] J. P. Ronzheimer,[1,2] M. Schreiber,[1,2] S. S. Hodgman,[1,2] T. Rom,[1,2] I. Bloch,[1,2] U. Schneider[1,2]*

Ultra-cold boson gas in optical lattice 10^5 $^{39}\mathrm{K}$ atoms

$$H = -J\sum_{\langle i,j\rangle} \hat{b}_i^\dagger \hat{b}_j + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) + V\sum_i \mathrm{r}_i^2 \hat{n}_i$$

via Feshbach resonance

- U>0: repulsive interactions
- U<0: attractive interactions

Claim: for U,V<0 spectrum bounded from above, population inversion in momentum space $\Rightarrow T < 0$

SCIENCE VOL 339 4 JANUARY 2013

Negative Absolute Temperature for Motional Degrees of Freedom

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Because negative temperature systems can absorb entropy while releasing energy, they give rise to several counterintuitive effects, such as Carnot engines with an efficiency greater than unity (*4*). Through a stability analysis for thermodynamic equilibrium, we showed that negative temperature states of motional degrees of freedom necessarily possess negative pressure (*9*) and are thus of fundamental interest to the description of dark energy in cosmology, where negative pressure is required to account for the accelerating expansion of the universe (*10*).

✓ Carnot efficiencies >1

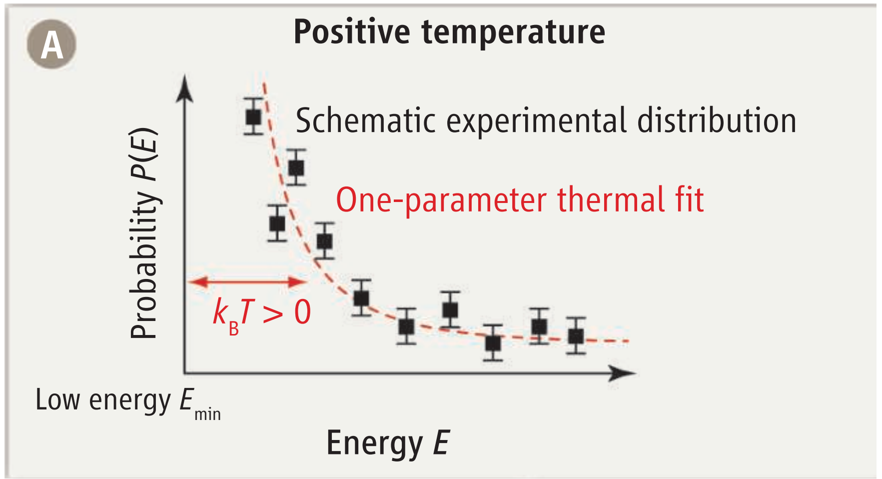
✓ Dark Energy

Measuring T_B *vs.* T_G

arxiv: 1304.2066

One-particle distribution

$$\rho_1 = \mathrm{Tr}_{N-1}[\rho_N] = \frac{\mathrm{Tr}_{N-1}[\delta(E-H_N)]}{\omega_N}$$



Steepest-descent approximation

$$\rho_1 = \exp[\ln \rho_1] \quad \Rightarrow \quad p_\ell \simeq \frac{e^{-E_\ell/(k_\mathrm{B}T_\mathrm{B})}}{Z}, \qquad Z = \sum_\ell e^{-E_\ell/(k_\mathrm{B}T_\mathrm{B})}.$$

see e.g. Huang's textbook

features T_B and not T_G

$\Rightarrow$ one-particle thermal fit does not give absolute $T = T_\mathrm{G}$

Generally

$$\boxed{T_\mathrm{B} = \frac{T_\mathrm{G}}{1 - k_\mathrm{B}/C}}$$

$$C = \left(\frac{\partial T_\mathrm{G}}{\partial E}\right)^{-1}$$

OPEN SYSTEMS

$$H(\lambda(t)) \longrightarrow H_{SYSTEM}(\lambda(t)) + H_{BATH} + H_{S\text{-}B}$$

canonical ensemble

$\varrho^T = \delta(E^T - H^T(\xi, Z)) / \omega^T(E^T, Z) \Rightarrow P(E^S | E^T, Z) = \dfrac{\omega^S(E^S)\,\omega^B(E^T - E^S)}{\omega_T(E^T)}$

$E^T = E^S + E^B$

$$= \frac{\omega^S(E^S)}{\varepsilon\,\omega^T(E^T)} \exp\left[\frac{S_B^B(\overbrace{E^T - E^S}^{E^B})}{k_B}\right]$$

NEXT: $S_B^B(E^T - E^S) = S_B^B(\bar{E}^B) + \dfrac{1}{T_B^B(\bar{E}_B)}(E^T - E^S - \bar{E}^B) + \ldots,$

$$\rightsquigarrow \quad = \frac{\omega^S(E^S)}{\varepsilon\,\omega^T(E^T)} \exp\left[\frac{S_B^B(\bar{E}^B)}{k_B} + \frac{(E^T - \bar{E}^B) - E^S}{k_B T_B^B(\bar{E}^B)} + \ldots\right]$$

with $+ \ldots \to 0$! $(\partial^2 S_B^B / \partial^2 E^B) = -1/T_B^2 C_B^B)$

$$\Rightarrow \quad P(E^S | E^T, Z) = \frac{\omega^S(E^S)}{Z_{can}} \exp\left[-\frac{E^S}{k_B T_B^B(\bar{E}^B)}\right]$$

note: $T_B^B(\bar{E}_B) \stackrel{?}{=} T_B^B(E^T)$; IF "normal": $T_B^B = T_G^B = T_G^S = T_G^T$

Take-Home-Messages:
T.D. of finite systems

- Use Gibbs-Hertz- Entropy

- finite system-bath coupling

partition function: $\mathcal{Z} = \mathcal{Z}_{S+B}/\mathcal{Z}_B$

Then, all Grand Laws of T.D. are obeyed!

- temperature of a nanosystem does not fluctuate

Conclusions

- population inversion $\Longrightarrow$ microcanonical
- bounded spectrum $\Longrightarrow$ ensembles not equivalent
- consistent thermostatistics $\Longrightarrow$ Gibbs entropy
- temperature always positive (‘by construction’)
- no Carnot efficiencies > 1
- please correct textbooks & lecture notes

[redacted]

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Thermodynamic laws in isolated systems

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**** 23 pages ****

Erunt multi qui, postquam mea scripta legerint, non ad contemplandum utrum vera sint quae dixerim, mentem convertent, sed solum ad disquirendum quomodo, vel iure vel iniuria, rationes meas labefactare possent.

G. Galilei, *Opere* (Ed. Naz., vol. I, p. 412)

There will be many who, when they will have read my paper, will apply their mind, not to examining whether what I have said is true, but only to seeking how, by hook or by crook, they could demolish my arguments.

Vol. 30 (1991) *REPORTS ON MATHEMATICAL PHYSICS* No. 1

THE MANY FACETS OF ENTROPY

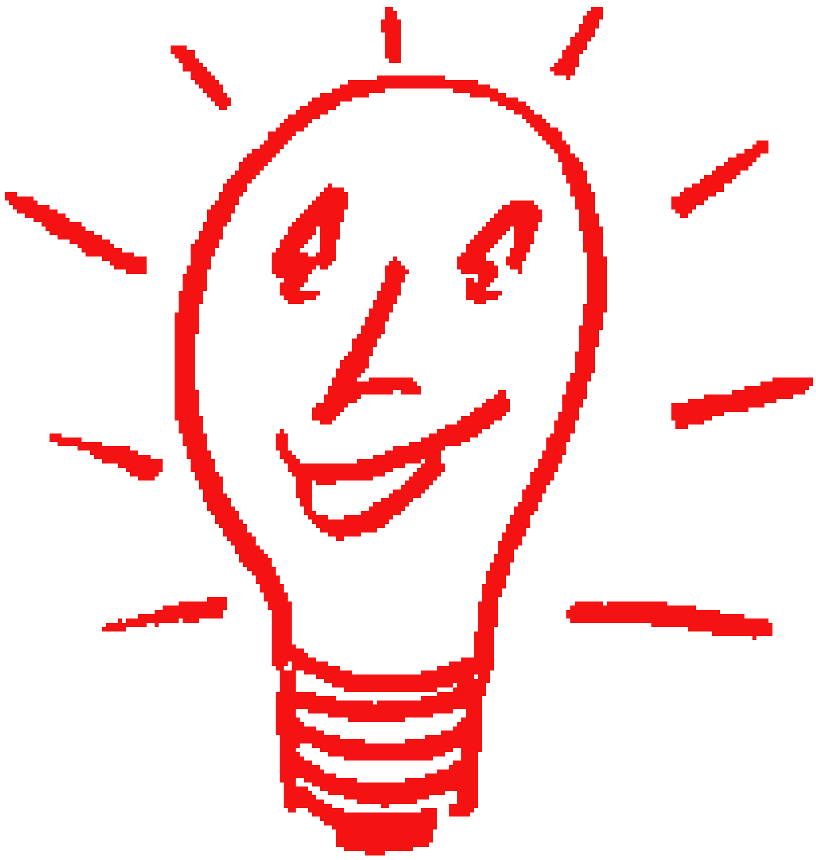
A. WEHRL

Institut für Theoretische Physik, Universität Wien, Baltzmanngane 5, A-1090, Wien, Austria

(*Received December 31, 1990*)

Several notions of entropy are discussed: classical entropies (Boltzmann, Gibbs, Shannon, quantum-mechanical entropy, skew entropy, among other notions as well as classical and quantum-mechanical dynamical entropies.

A QUESTION ?

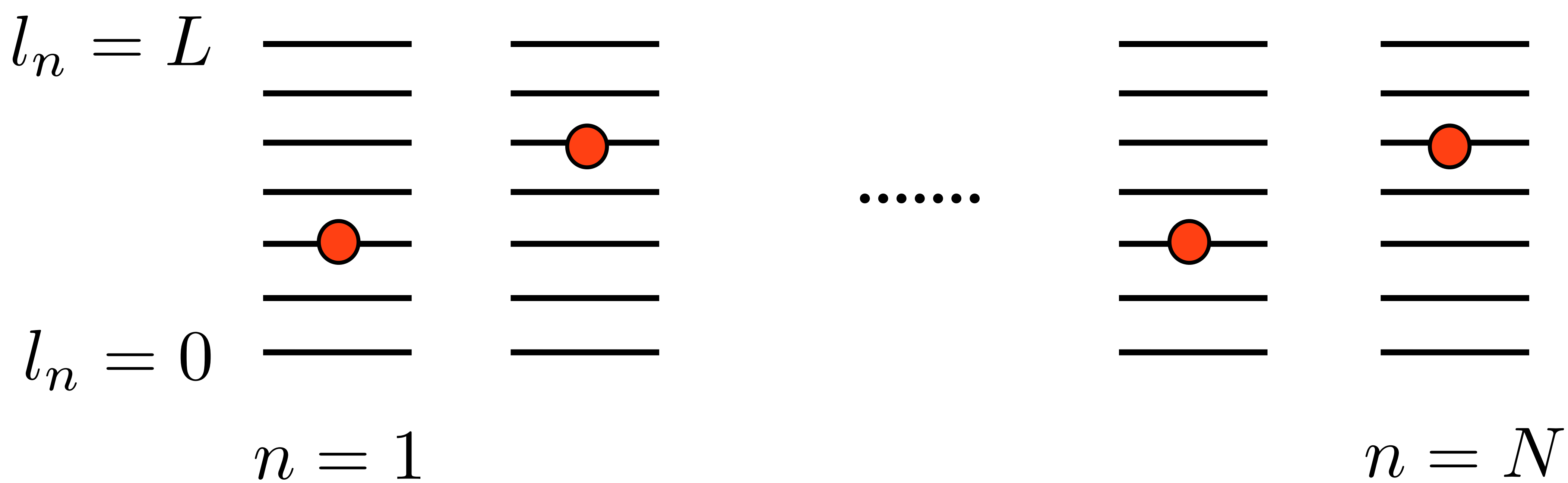


Generic spin or oscillator model

arxiv: 1304.2066

$$H_N \simeq \sum_{n=1}^{N} h_n, \qquad E_{\ell_n} = \epsilon \ell_n \qquad \ell_n = 0, 1 \ldots, L$$

$$E_\Lambda = \epsilon(\ell_1 + \ldots + \ell_N) \qquad 0 \leq E_\Lambda \leq E_+ = \epsilon L N$$



OPEN SYSTEMS

$$\mathcal{H}(\lambda_t) = \mathcal{H}_S(\lambda_t) + \mathcal{H}_B + \mathcal{H}_{S-B}(\cancel{\lambda_t}\,)$$

no

CLASSICAL WORK: $\mathcal{H}(\Gamma_\tau;\lambda_\tau) - \mathcal{H}(\Gamma_0;\lambda_0)$

with $\frac{d\mathcal{H}}{dt} = \frac{\partial \mathcal{H}}{\partial t} = \frac{\partial \mathcal{H}}{\partial \lambda}\dot{\lambda} = \frac{\partial \mathcal{H}_S}{\partial \lambda}\dot{\lambda}$ $\Rightarrow$ $= \int_0^\tau dt\, \underbrace{\frac{\partial \mathcal{H}_S^*(\Gamma_t^S;\lambda(t))}{\partial \lambda(t)}}_{=\frac{\partial \mathcal{H}_S}{\partial \lambda}} \dot{\lambda}(t)$

! NOT SO ! FOR QUANTUM

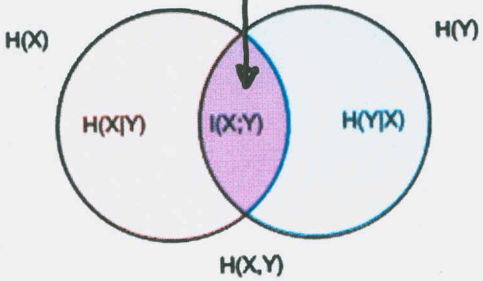
by the way: $\mathcal{H}_S^*(\Gamma_\tau^S;\lambda_\tau) - \mathcal{H}_S^*(\Gamma_0^S;\lambda_0) = \int_0^\tau dt\, \dot{\lambda}\, \frac{\partial \mathcal{H}_S(\Gamma_t^S;\lambda_t)}{\partial \lambda(t)} + \int_0^\tau dt\, \dot{\Gamma}_t^S \frac{\partial \mathcal{H}_S^*(\Gamma_t^S;\lambda_t)}{\partial \Gamma_t^S}$

2-nd LAW - WORK

? ?

Conditional Entropy

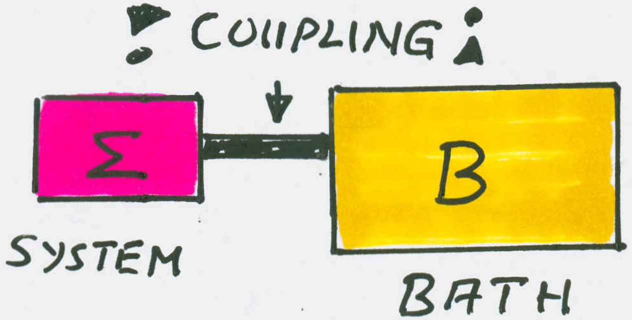
$$I(x;y) = H(x,y) - H(x|y) - H(y|x)$$



$$H(y|x) = -\sum_{x,y} p(x,y) \ln p(x,y) - \left(-\sum_{x} p(x) \ln p(x)\right) = -\sum_{x,y} p(x,y) \ln p(y|x) \geq 0$$

Quantum Conditional Entropy

von NEUMANN: $S_{vN}(\varrho_\Sigma) = -Tr\, \varrho_\Sigma \ln \varrho_\Sigma$



$$S_\Sigma = S_{vN}\left(\varrho^{can}_{\Sigma\times B}\right) - S_{vN}\left(\varrho^{can}_{B}\right)$$

can. thermod. entropy

$$\overset{?!}{=} S_{vN}\left(\varrho^{can}_{\Sigma\times B}\right) - S_{vN}\left(\varrho_B = Tr_\Sigma\, \varrho^{can}_{\Sigma\times B}\right)$$

quantum cond. entropy

$\uparrow \neq \varrho_B^{can}$

Quantum Hamiltonian of Mean Force

$$Z_S(t) := \frac{Y(t)}{Z_B} = \mathrm{Tr}_S e^{-\beta H^*(t)}$$

where

$$H^*(t) := -\frac{1}{\beta} \ln \frac{\mathrm{Tr}_B e^{-\beta(H_S(t)+H_{SB}+H_B)}}{\mathrm{Tr}_B e^{-\beta H_B}}$$

also

$$\frac{e^{-\beta H^*(t)}}{Z_S(t)} = \frac{\mathrm{Tr}_B e^{-\beta H(t)}}{Y(t)}$$

M. Campisi, P. Talkner, P. Hänggi, Phys. Rev. Lett. **102**, 210401 (2009).

Strong coupling: Example

System: Two-level atom; "bath": Harmonic oscillator

$$H = \frac{\epsilon}{2}\sigma_z + \Omega\left(a^\dagger a + \frac{1}{2}\right) \quad + \chi\sigma_z\left(a^\dagger a + \frac{1}{2}\right)$$

$$H^* = \frac{\epsilon^*}{2}\sigma_z + \gamma$$

$$\epsilon^* = \epsilon + \chi + \frac{2}{\beta}\operatorname{artanh}\left(\frac{e^{-\beta\Omega}\sinh(\beta\chi)}{1 - e^{-\beta\Omega}\cosh(\beta\chi)}\right)$$

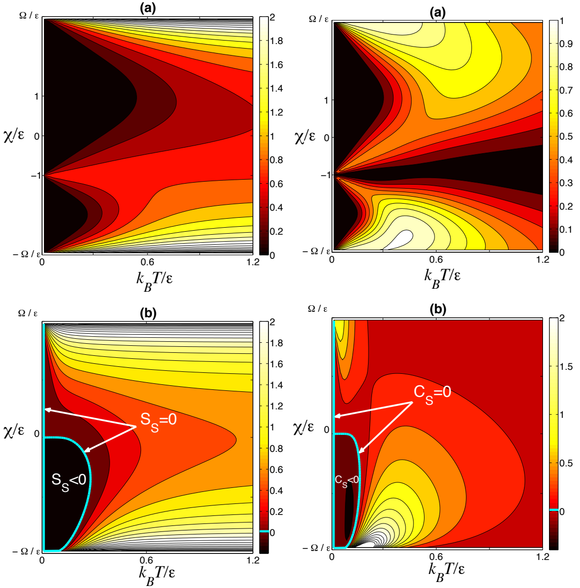
$$\gamma = \frac{1}{2\beta}\ln\left(\frac{1 - 2e^{-\beta\Omega}\cosh(\beta\chi) + e^{-2\beta\Omega}}{(1 - e^{-\beta\Omega})^2}\right)$$

$$Z_S = \mathrm{Tr} e^{-\beta H^*} \quad F_S = -k_b T \ln Z_S$$

$$S_S = -\frac{\partial F_S}{\partial T} \quad C_S = T\frac{\partial S_S}{\partial T}$$

M. Campisi, P. Talkner, P. Hänggi, J. Phys. A: Math. Theor. **42** 392002 (2009)

Entropy and specific heat



$\Omega/\epsilon = 3$

$\Omega/\epsilon = 1/3$

Tampering with the 2-nd Law

using generalized (non thermodynamic)

entropies is not the best idea

→ doomed to yield unphysical results

(Landauer limit,...)

On the Use and Abuse of THERMODYNAMIC Entropy

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