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Thermodynamic Derivation of the Fluctuation Theorem and Jarzynski Equality

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A thermodynamic expression for the analog of the canonical ensemble for nonequilibrium systems is described based on a purely information theoretical interpretation of entropy. It is shown that this nonequilibrium canonical distribution implies some important results from nonequilibrium thermodynamics, specifically, the fluctuation theorem and the Jarzynski equality. Those results are therefore expected to be more widely applicable, for example, to macroscopic systems.

1. Introduction

The derivations of the fluctuation theorem [1, 2] and the Jarzynski equality [3] appear to depend on the underlying microscopic Hamiltonian dynamics. From this it would follow that these theorems are only relevant to microscopic systems, with their associated definitions of entropy and temperature. In contrast, a statistical mechanical description of macroscopic systems often depends on more general forms of entropy, primarily information entropy [4–6]. Two notable examples from fluid dynamics are the statistical mechanics of point vortices [7] and the statistical mechanics of two-dimensional incompressible flows [8]. In such cases, temperature is defined in terms of the change of entropy with the energy of the system [9] or, equivalently, in terms of the Lagrange multiplier for the energy under the maximization of entropy at a given expectation value of the energy [10].

The theoretical background can be found in [10], where it is shown that this information theoretical interpretation reproduces the statistical mechanics based on Gibbs entropy but furthermore gives a justification of the Gibbs formulation as a statistical inference problem under limited knowledge of the system. Of note is that the entropy only has meaning in relation to the macroscopic constraints on the system (indicated by the subscripts $A$ and $B$), constraints which can be arbitrarily complex and prescriptive, as may be the case for climate science.

Here we demonstrate that the information-theoretical definition of entropy implies the fluctuation theorem and the Jarzynski equality. It is shown that these results are due to the counting properties of entropy rather than the dynamics of the underlying system. As such, both these results are applicable to a much wider class of problems, specifically, macroscopic systems for which we can define an entropy and which are thermostated in some general sense.

The central tenet is that for two states $A$ and $B$ of a system, defined by two sets of macroscopic parameters, the ratio of the probabilities $p_B/p_A$ for the system to be in either state is

\[ \frac{p_B}{p_A} = \exp\left(\frac{\Delta_{AB}S}{k}\right), \quad (1) \]

with $\Delta_{AB}S$ being the difference in entropy between the states $B$ and $A$. This is essentially the Boltzmann definition of entropy: entropy is a counting property of the system. The theoretical background can be found in [10], where it is shown that this information theoretical interpretation reproduces the statistical mechanics based on Gibbs entropy but furthermore gives a justification of the Gibbs formulation as a statistical inference problem under limited knowledge of the system. Of note is that the entropy only has meaning in relation to the macroscopic constraints on the system (indicated by the subscripts $A$ and $B$), constraints which can be arbitrarily complex and prescriptive, as may be
needed for systems far from equilibrium. In an information-theoretical setting the previous definition of entropy is
equivalent to the principle of indifference: the absence of any distinguishing information between microscopic states
within any of the macroscopic states A or B is equivalent to equal prior (prior to obtaining additional macroscopic
constraints) probabilities for the microscopic states [16]. Note also that we do not need to specify precisely at this point
how the states are counted, or how an invariant measure can be defined on the phase space confined by A or B. The
principle of indifference does not imply that all states are assumed equally probable; it is a statement that we cannot
priori assume equally probable; it is a statement that we cannot
further information. The principle of

2. A General Form for the Canonical Ensemble

Following Boltzmann, we define the entropy \( S_A \) as the
logarithm of the number of states accessible to a system
under given macroscopic constraints \( A \). For an isolated
system, the entropy is related to the size \( \Phi_A \) of the accessible
phase space:

\[
S_A = k \ln \Phi_A. \tag{2}
\]

For a classical gas system, \( A \) is defined by the energy \( U \),
volume \( V \) and molecule number \( N \), the phase space size
\( \Phi_A \) is the hyperarea of the energy shell, and it defines
the usual microcanonical ensemble. For more complicated
systems, where \( A \) may include several macroscopic order
parameters, the energy shell becomes more confined; in the
following we will still refer to the accessible phase space
under constraints \( A \) as the energy shell. The hyperarea \( \Phi_A \)
is nondimensionalised such that \( \Phi_A(U)dU \) is proportional
to the number of states between energies \( U \) and \( U + dU \). We
will not consider other multiplicative factors which make the
argument of the logarithm nondimensional; these contribute
an additive entropy constant which will not be of interest to
us here. Note also that the microcanonical ensemble does not
include a notion of equilibrium: the system is assumed to be
insulated, so it cannot equilibrate with an external system.
It just moves around on the energy shell (defined by \( A \)) and
the principle of indifference implies that all states, however
improbable from a macroscopic point of view, are members
of the ensemble. Of course, the number of unusual states
(say, with nonuniform macroscopic properties not defined
by \( A \)) is much lower than the number of regular states (say,
with uniform macroscopic density) for macroscopic systems.
Only for small systems, the distinction becomes important
but it does not invalidate the previous formal definition
of entropy. The previous definition of entropy also ensures
that entropy is an extensive property such that for two
independent systems considered together the total entropy
is the sum of the individual entropies, \( S = S_1 + S_2 \). The
Boltzmann constant \( k \) ensures dimensional compatibility
with the classical thermodynamic entropy when the usual
equilibrium assumptions are made [10, 17].

The hyperarea of the energy shell, and thus the entropy,
can be a function of several variables which are set as external
constraints, such as the total energy \( U \), system volume, \( V \), or
particle number \( N \) for a simple gas system. For the canonical
ensemble we consider a system that can exchange energy with
some reservoir. We consider here only a theoretical canonical
ensemble in that we consider the coupling between the two
systems to be weak such that the interaction energy vanishes
compared to the relevant energy fluctuations in the system.

First, we need to define what a reservoir is. Following
equilibrium thermodynamics, we formally define an inverse
temperature \( \beta = (kT)^{-1} \) as

\[
\beta = \frac{1}{k} \frac{\partial S}{\partial U} = \frac{1}{\Phi} \frac{\partial \Phi}{\partial U}. \tag{3}
\]

We make no claim about the equality of \( \beta \) and the classical
equilibrium inverse temperature; \( \beta \) is the expansivity of
phase space with energy and as such can be defined for any
system, whether it is in thermodynamic equilibrium or not.
When an isolated system is prepared far from equilibrium
(e.g., when it has a local equilibrium temperature which
varies over the system), then \( \beta \) is still uniquely defined for
the system as a nonlocal property of the energy shell that the
system resides on. Because both energy and entropy in the
weak coupling limit are extensive quantities, \( \beta \) must be an
intensive quantity.

Now consider a large isolated system \( R \) with total
(internal) energy \( UR \). Let this system receive energy \( U' \)
from the environment. By expanding its entropy \( SR \) in powers of
\( U \), we can then write the entropy of this large system as

\[
SR(U_R + U') = SR(U_R) + kU' \left( \beta + \frac{1}{2} U' \frac{\partial \beta}{\partial U} + \mathcal{O}(U'^2) \right). \tag{4}
\]

We see that for finite \( U' \), \( (\partial \beta/\partial U)^{-1} \) has to be an extensive
quantity. But that means that for a very large system \( \partial \beta/\partial U = \mathcal{O}(N^{-1}) \), where \( N \) is a measure of the size of the system (such
as particle number). For a classical thermodynamic system
\( \partial \beta/\partial U = -k\beta^2/C_V \) with \( C_V \) the heat capacity at constant
volume. We conclude that for a very large system \( (N \rightarrow \infty) \),
the entropy equals

\[
SR(U_R + U') = SR(U_R) + k\beta U' \tag{5}
\]

for all relevant, finite energy exchanges \( U' \). This expression
for the entropy defines a reservoir. The size of the energy shell
accessible to the reservoir is, for all relevant energy exchanges
\( U' \), exactly proportional to \( \exp(\beta U') \), with \( \beta \) an intensive
and constant property of the reservoir. We do not require
the reservoir to be in thermodynamic equilibrium. A change
of energy in the reservoir pushes the reservoir to a different
energy shell \( A' \); the functional dependence of the size of the
energy shell with energy defines the inverse temperature \( \beta \),
as in (3). However, it is not assured that a small and fast
thermometer would measure an inverse temperature equal
to \( \beta \) at some point in the reservoir; only if the reservoir is
allowed to equilibrate, its inverse temperature is everywhere equal to $\beta$. Of course, this is how the temperature of a classical reservoir is determined in practice.

Now suppose that a system of interest has energy $U_0$. We then allow it to exchange heat $U$ with a reservoir. If the system has energy $U_0 + U$, the reservoir must have given up energy $U$. We can write the hyperarea of the energy shell of the system $\Phi_0$ as a function of $U$. The total entropy of the system plus reservoir $R$ can then be written as a function of the exchange energy, $U$, as

$$S = S_0(U) + S_R(U_R) - k\beta U, \quad (6)$$

with $S_0 = k\ln \Phi_0$. The number of states at each level of exchange energy therefore is proportional to

$$\Phi(U) \propto \Phi_0(U) \exp(-\beta U), \quad (7)$$

where we omitted proportionality constants related to the additive entropy constants. Nowhere we assume that the system is in equilibrium with the reservoir. This means that $\Phi(U)$ is the relevant measure to construct an ensemble average for the system, even for far-from-equilibrium systems. Even the reservoir can be locally out of equilibrium, as discussed previously. We have also made no reference to the size of the system of interest, as long as it is much smaller than the reservoir. However, in contrast to systems in thermodynamic equilibrium, there is no guarantee that the extensive macroscopic variables, such as $U$, $V$, or $N$, define the state of the system in any reproducible sense. To fully define an out-of-equilibrium system we need to introduce order parameters that can describe the nonequilibrium aspects of the system.

The previous density is an integrated version of the usual canonical distribution. The size of the energy shell of the system of interest, $\Phi_0$, can be written as an integral over states $\Gamma$ such that

$$\Phi_0(U) = \int_{H_0(\Gamma) = U} d\Gamma, \quad (8)$$

with $H_0$ being the Hamiltonian of the system of interest. With this definition, the density in (7) reduces to the usual canonical distribution $\exp(-\beta H_0(\Gamma))$ for states $\Gamma$. We will not make further use of this microscopic version of the density.

3. Fluctuation Theorems

The canonical density in (7) can be expanded by parametrizing each energy shell with some continuous coordinate $v$ so that every part of phase space has coordinates $(U, v)$. The coordinate $v$ is again a macroscopic coordinate so that any combination $(U, v)$ can correspond to many microscopic states. At each value of $v$ the differential $\phi(U, v) dU dv$ is proportional to the number of states between coordinate values $U$ and $U + dU$, and $v$ and $v + dv$, and it is normalized such that

$$\int \phi(U, v) dv = \Phi_0(U). \quad (9)$$

The parametrization is arbitrary at this point and can be chosen such as to divide the phase space in as fine a structure as desired for a given application. We can define an entropy $S_0(U, v)$ again as the logarithm of the number of available states for the system of interest corresponding to the subset of phase space defined by $(U, v)$:

$$S_0(U, v) = k\ln \phi(U, v). \quad (10)$$

Now consider a process that occurs on the energy shell $U$ where some variable changes from $A \rightarrow B$. On the parametrized energy shell this corresponds to a coordinate shift from $v(A) \rightarrow v(B)$. The number of corresponding states changes from $\phi(U, v(A)) \rightarrow \phi(U, v(B))$. We can use detailed balance to express the ratio of the probability of making this transition to the probability of making the reverse transition as the ratio of the number of states at $(U, v(A))$ to the number of states at $(U, v(B))$:

$$\frac{p_{A\rightarrow B}}{p_{B\rightarrow A}} = \frac{\phi(U, v(B))}{\phi(U, v(A))} = \exp\left(\frac{\Delta_{AB}S}{k}\right), \quad (11)$$

where $\Delta_{AB}S/k = S_0(U, v(B)) - S_0(U, v(A))$. If, in addition, during the process $A \rightarrow B$ the energy of the system of interest changes from $U_A \rightarrow U_B$ through exchange with the reservoir, then the previous ratio of probabilities can still be expressed as $\exp(\Delta_{AB}S/k)$ but now with

$$\Delta_{AB}S = S_0(U_B, v(B)) - S_0(U_A, v(A)) - k\beta(U_B - U_A). \quad (12)$$

We can always write the entropy change of the system of interest as the sum of the entropy change due to heat exchange with the reservoir and an irreversible entropy change associated with uncompensated heat [14, 18], namely, $S_0(U_B, v(B)) - S_0(U_A, v(A)) = k\beta(U_B - U_A) + \Delta S_0$. We thus conclude that $\Delta_{AB}S = \Delta S_0$; that is, the relevant entropy change in (11) equals the irreversible entropy change of the system of interest. So for processes that occur either on or across energy shells, we have

$$\frac{p_{A\rightarrow B}}{p_{B\rightarrow A}} = \exp\left(\frac{\Delta S_0}{k}\right), \quad (13)$$

with $\Delta S_0$ being the irreversible entropy change of the system in a process $A \rightarrow B$. The right-hand side of this equation is only dependent on the irreversible entropy change $\Delta S_0$ between the two states of the system of interest. So this equation must be true for any pair of states $(A, B)$ that are related by the same irreversible entropy change. We thus arrive at the fluctuation theorem [1, 2]:

$$\frac{p(\Delta S)}{p(-\Delta S)} = \exp\left(\frac{\Delta S}{k}\right), \quad (14)$$

with $p(\Delta S)$ being the probability that the system of interest makes a transition with irreversible entropy change of $\Delta S$ and $p(-\Delta S)$ being the probability for the opposite change.

The fluctuation theorem applies to spontaneous processes that occur in thermostated but otherwise isolated systems. We next consider processes that occur when we modify the system of interest by changing some external
macroscopic parameters. The entropy of the energy shell $U$ is then also a function of some parameter $\lambda$, namely, $S = S_\lambda(U, \nu)$. Without loss of generality we set $\lambda = 0$ at $A$ and $\lambda = 1$ at $B$. In this case the irreversible entropy change in (13) is

$$\frac{\Delta S}{k} = S_1(U_B, \nu(B)) - S_0(U_A, \nu(A)) - k\beta(U_B - U_A).$$

Apart from this, there is no change in the considerations leading to the fluctuation theorem. By definition, thermostated systems that receive work $W_{AB}$ from their environment have an irreversible entropy change equal to

$$\frac{\Delta S}{k} = \beta(W_{AB} - \Delta_{AB}F),$$

with $\Delta_{AB}F$ being the change in free energy going from $A$ to $B$. Recognising that the right-hand side is again only a function of the difference between the two states, we arrive at the Crooks fluctuation theorem [19]:

$$p_{01}(W) = \exp(\beta(W - \Delta_{01}F)),$$

with $p_{01}(W)$ being the probability that the system absorbs work $W$ when $\lambda$ changes from 0 to 1, and $p_{10}(-W)$ being the probability that the system performs work $W$ when $\lambda$ changes in reverse from 1 to 0. Because the transition probabilities can be normalised with respect to the exchanged work, it is straightforward to use this equation to show that the expectation value of $\exp(-\beta(W - \Delta_{01}F))$ equals unity, or equivalently,

$$\langle \exp(-\beta W) \rangle = \exp(-\beta\Delta_{01}F).$$

This is the Jarzynski equality [3].

The consistency of the previous argument is strengthened by the following independent route to calculate free energy changes. The phase space measure $\Phi(U)$ can be normalised with the partition function $Z_\lambda$:

$$Z_\lambda = \int \Phi_\lambda(U) \exp(-\beta U) dU,$$

where $\Phi_\lambda(U)$ is proportional to the number of accessible states of the isolated system of interest when the external parameter is set to $\lambda$. The equilibrium free energy for the thermostated system is

$$F_\lambda = -\beta^{-1} \ln Z_\lambda.$$

Next we consider what happens to the equilibrium free energy of the system when we vary $\lambda$ from 0 to 1. The partition function at $\lambda = 1$ satisfies

$$Z_1 = \int \Phi_1(U) \exp(-\beta U) dU = \int \Phi_0(U) \exp(\frac{\Delta S}{k}) \exp(-\beta U) dU = Z_0 \langle \exp(\frac{\Delta S}{k}) \rangle,$$

where $\langle \cdot \rangle$ denotes an ensemble average over the initial ensemble, and $\Delta S = k \ln(\Phi_1(U)/\Phi_0(U))$. As before, the entropy change can be written as the sum of the entropy change due to heat exchange with the reservoir and the irreversible entropy change due to uncompensated heat. Because the system plus the reservoir is thermally insulated, any heat given to the reservoir must be compensated by work performed by the external parameter change. The entropy change can therefore be written as $\langle \exp(\Delta S/k) \rangle = (\exp(\Delta S/k - \beta W))$ so that we find

$$\frac{Z_1}{Z_0} = \langle \exp(\frac{\Delta S}{k} - \beta W) \rangle.$$

Because (16) is true for any microscopic realisation of the process, we find that the right-hand side of the previous equation is the same for every realisation and it is equal to $\exp(-\beta\Delta F)$. This is consistent with the equilibrium expression for the free energy, (20), from which follows that $\exp(-\beta\Delta F) = Z_1/Z_0$. The previous equation is only apparently in contradiction to the Jarzynski equality, (18). To arrive at the Jarzynski equality we recognise that (16) implies that $\langle \exp(\beta(\Delta F - W)) \rangle = \langle \exp(-\Delta S/k) \rangle = 1$, where the last equality follows from integrating the fluctuation theorem over all values of $\Delta S$.

4. Discussion

We have shown that the fluctuation theorem (14) and Jarzynski equality (18) follow from general counting properties of entropy and not from the underlying dynamics. As such we expect both results to be widely applicable to systems that are in some sense thermostated, that is, systems that are able to settle on a given expectation value for the total energy by interaction with a reservoir.

The climate system is potentially a nontrivial example of such a system: the incoming short-wave radiation from the Sun is depleted by long-wave (thermal infrared) radiation from the Earth to space. The corresponding equilibrium temperature is the bolometric temperature of the planet (about 255 K in case of the Earth [14]). (The bolometric radiation temperature of the Earth is substantially lower than the observed average surface temperature of about 288 K, because of the greenhouse effect of the atmosphere.) It is not obvious how to apply the fluctuation theorems to the climate system and how the entropy production in the climate system is related to the actual climate on Earth. For example, most of the entropy production in the climate system is due to degradation of radiation (e.g., [20]); namely, short wavelength visible sunlight is thermalized by molecular absorption into molecular thermal energy corresponding to long wavelength infrared radiation. This degradation of radiative energy is the main source of entropy production in the climate system, but as this entropy production only resides in the photon field, its relation to, for example, kinetic energy dissipation in the atmosphere is not clear. So from this example it appears that we need to select the relevant forms of entropy production before we can use it to make inferences about the climate system.
It remains to be seen whether the fluctuation theorems can be usefully applied to complex systems such as the climate, but we believe that the derivation presented here can pave the way for attempts in that direction.

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