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A Lower Bound on the Relative Entropy with Respect to a Symmetric Probability

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Abstract

Let ρ and μ be two probability measures on \mathbb{R} which are not the Dirac mass at 0. We denote by $H(\mu|\rho)$ the relative entropy of μ with respect to ρ . We prove that, if ρ is symmetric and μ has a finite first moment, then

$$H(\mu|\rho) \geq \frac{\left(\int_{\mathbb{R}} z d\mu(z)\right)^2}{2 \int_{\mathbb{R}} z^2 d\mu(z)},$$

with equality if and only if $\mu = \rho$. We give an application to the Curie-Weiss model of self-organized criticality.

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1 Introduction

Given two probability measures μ and ρ on \mathbb{R} , the relative entropy of μ with respect to ρ (or the Kullback-Leibler divergence of ρ from μ) is

$$H(\mu|\rho) = \begin{cases} \int_{\mathbb{R}} f(z) \ln f(z) d\rho(z) & \text{if } \mu \ll \rho \text{ and } f = \frac{d\mu}{d\rho} \\ +\infty & \text{otherwise,} \end{cases}$$

where $d\mu/d\rho$ denotes the Radon-Nikodym derivative of μ with respect to ρ when it exists. In this paper, we prove the following theorem:

Theorem 1. *Let ρ and μ be two probability measures on \mathbb{R} which are not the Dirac mass at 0. If ρ is symmetric and if μ has a finite first moment, then*

$$H(\mu|\rho) \geq \frac{\left(\int_{\mathbb{R}} z d\mu(z)\right)^2}{2 \int_{\mathbb{R}} z^2 d\mu(z)},$$

with equality if and only if $\mu = \rho$.

A remarkable feature of this inequality is that the lower bound does not depend on the symmetric probability measure ρ . We found the following related inequality in the literature (see lemma 3.10 of [1]): if ρ is a probability measure on \mathbb{R} whose first moment m exists and such that

$$\exists v > 0 \quad \forall \lambda \in \mathbb{R} \quad \int_{\mathbb{R}} \exp(\lambda(z - m)) d\rho(z) \leq \exp\left(\frac{v\lambda^2}{2}\right),$$

then, for any probability measure μ on \mathbb{R} having a first moment, we have

$$H(\mu|\rho) \geq \frac{1}{2v} \left(\int_{\mathbb{R}} z d\mu(z) - m\right)^2.$$

Our inequality does not require an integrability condition. Instead we assume that ρ is symmetric.

The proof of the theorem is given in the following section. It consists in relating the relative entropy $H(\cdot|\rho)$ and the Cramér transform I of (Z, Z^2) when Z is a random variable with distribution ρ . We then use an inequality on I which we proved initially in [2]. We give here a simplified proof of this inequality.

In section 3, we apply the inequality of theorem 1 to the Curie-Weiss model of self-organized criticality we designed in [2]. We prove that, if (X_n^1, \dots, X_n^n) has the distribution

$$d\tilde{\mu}_{n,\rho}(x_1, \dots, x_n) = \frac{1}{Z_n} \exp\left(\frac{1}{2} \frac{(x_1 + \dots + x_n)^2}{x_1^2 + \dots + x_n^2}\right) \mathbb{1}_{\{x_1^2 + \dots + x_n^2 > 0\}} \prod_{i=1}^n d\rho(x_i),$$

for any $n \geq 1$, and if ρ is symmetric with compact support and such that $\rho(\{0\}) < 1/\sqrt{e}$, then, for any continuous function $f : \mathbb{R} \rightarrow \mathbb{R}$,

$$\forall \varepsilon > 0 \quad \lim_{n \rightarrow \infty} \tilde{\mu}_{n,\rho} \left(\left| \frac{1}{n} \sum_{k=1}^n f(X_n^k) - \int_{\mathbb{R}} f(z) d\rho(z) \right| \geq \varepsilon \right) = 0.$$

2 Proof of the theorem

Let ρ and μ be two probability measures on \mathbb{R} which are not the Dirac mass at 0. We first recall that $H(\mu|\rho) \geq 0$, with equality if and only if $\mu = \rho$.

We assume that ρ is symmetric and that μ has a finite first moment. We denote

$$\mathcal{F}(\mu) = \frac{\left(\int_{\mathbb{R}} z d\mu(z) \right)^2}{2 \int_{\mathbb{R}} z^2 d\mu(z)}.$$

If $\mu = \rho$ then $\mathcal{F}(\mu) = 0 = H(\mu|\rho)$. From now onwards we suppose that $\mu \neq \rho$. If the first moment of μ vanishes or if its second moment is infinite, then we have $\mathcal{F}(\mu) = 0 < H(\mu|\rho)$. Finally, if μ is such that $H(\mu|\rho) = +\infty$, then Jensen's inequality implies that

$$\mathcal{F}(\mu) \leq 1/2 < H(\mu|\rho).$$

In the following, we suppose that

$$\int_{\mathbb{R}} z d\mu(z) \neq 0, \quad \int_{\mathbb{R}} z^2 d\mu(z) < +\infty,$$

and that $H(\mu|\rho) < +\infty$. This implies that $\mu \ll \rho$ and we set $f = d\mu/d\rho$. It follows from Jensen's inequality that, for any μ -integrable function Φ ,

$$\int_{\mathbb{R}} \Phi d\mu - H(\mu|\rho) = \int_{\mathbb{R}} \ln \left(\frac{e^\Phi}{f} \right) d\mu \leq \ln \int_{\mathbb{R}} \frac{e^\Phi}{f} d\mu = \ln \int_{\mathbb{R}} e^\Phi d\rho.$$

As a consequence

$$\sup_{\Phi \in L^1(\mu)} \left\{ \int_{\mathbb{R}} \Phi d\mu - \ln \int_{\mathbb{R}} e^\Phi d\rho \right\} \leq H(\mu|\rho).$$

In order to make appear the first and second moments of ρ , we consider functions Φ of the form $z \mapsto uz + vz^2$, $(u, v) \in \mathbb{R}^2$. This way we obtain

$$I \left(\int_{\mathbb{R}} z d\mu(z), \int_{\mathbb{R}} z^2 d\mu(z) \right) \leq H(\mu|\rho),$$

where

$$\forall (x, y) \in \mathbb{R}^2 \quad I(x, y) = \sup_{(u, v) \in \mathbb{R}^2} \left\{ ux + vy - \ln \int_{\mathbb{R}} e^{uz+ vz^2} d\rho(z) \right\}.$$

The function I is the Cramér transform of (Z, Z^2) when Z is a random variable with distribution ρ . In our paper dealing with a Curie-Weiss model of self-organized criticality [2], we proved with the help of the following inequality that, under some integrability condition, the function $(x, y) \mapsto I(x, y) - x^2/(2y)$ has a unique global minimum on $\mathbb{R} \times]0, +\infty[$ at $(0, \int x^2 d\rho(x))$.

Proposition 2. *If ρ is a symmetric probability measure which is not the Dirac mass at 0, then*

$$\forall x \neq 0 \quad \forall y \neq 0 \quad I(x, y) > \frac{x^2}{2y}.$$

We present here a proof of this proposition which is simpler than in [2].

Proof. Let $x \neq 0$ and $y \neq 0$. By definition of $I(x, y)$, we have

$$\begin{aligned} I(x, y) &\geq x \times \frac{x}{y} + y \times \left(-\frac{x^2}{2y^2}\right) - \ln \int_{\mathbb{R}} \exp\left(\frac{xz}{y} - \frac{x^2 z^2}{2y^2}\right) d\rho(z) \\ &= \frac{x^2}{2y} - \ln \int_{\mathbb{R}} \exp\left(\frac{xz}{y} - \frac{x^2 z^2}{2y^2}\right) d\rho(z). \end{aligned}$$

Let $(s, t) \in \mathbb{R}^2$. By using the symmetry of ρ , we obtain

$$\begin{aligned} \int_{\mathbb{R}} \exp(sz - tz^2) d\rho(z) &= \int_{\mathbb{R}} \exp(-sz - tz^2) d\rho(z) \\ &= \frac{1}{2} \left(\int_{\mathbb{R}} \exp(sz - tz^2) d\rho(z) + \int_{\mathbb{R}} \exp(-sz - tz^2) d\rho(z) \right) \\ &= \int_{\mathbb{R}} \cosh(sz) \exp(-tz^2) d\rho(z). \end{aligned}$$

We choose now $t = s^2/2$. We have the inequality

$$\forall u \in \mathbb{R} \setminus \{0\} \quad \cosh(u) \exp(-u^2/2) < 1.$$

Since ρ is not the Dirac mass at 0, the above inequality implies that

$$\forall s \neq 0 \quad \int_{\mathbb{R}} \cosh(sz) \exp\left(-\frac{s^2 z^2}{2}\right) d\rho(z) < 1.$$

We finally choose $s = x/y$ and we get

$$\int_{\mathbb{R}} \exp\left(\frac{xz}{y} - \frac{x^2 z^2}{2y^2}\right) d\rho(z) < 1.$$

As a consequence

$$I(x, y) \geq \frac{x^2}{2y} - \ln \int_{\mathbb{R}} \exp\left(\frac{xz}{y} - \frac{x^2 z^2}{2y^2}\right) d\rho(z) > \frac{x^2}{2y},$$

which is the desired inequality. □

By applying the above proposition with

$$x = \int_{\mathbb{R}} z d\mu(z) \neq 0, \quad y = \int_{\mathbb{R}} z^2 d\mu(z) \in]0, +\infty[,$$

we obtain

$$H(\mu|\rho) \geq I\left(\int_{\mathbb{R}} z d\mu(z), \int_{\mathbb{R}} z^2 d\mu(z)\right) > \mathcal{F}(\mu).$$

This ends the proof of theorem 1.

3 Application to the Curie-Weiss model of SOC

In [2], we designed the following model: Let ρ be a probability measure on \mathbb{R} , which is not the Dirac mass at 0. We consider an infinite triangular array of real-valued random variables $(X_n^k)_{1 \leq k \leq n}$ such that for all $n \geq 1$, (X_n^1, \dots, X_n^n) has the distribution $\tilde{\mu}_{n,\rho}$, where

$$d\tilde{\mu}_{n,\rho}(x_1, \dots, x_n) = \frac{1}{Z_n} \exp\left(\frac{1}{2} \frac{(x_1 + \dots + x_n)^2}{x_1^2 + \dots + x_n^2}\right) \mathbb{1}_{\{x_1^2 + \dots + x_n^2 > 0\}} \prod_{i=1}^n d\rho(x_i),$$

and Z_n is the renormalization constant. In [2] and [4], we proved that this model exhibits self-organized criticality: for a large class of symmetric distributions, we proved the fluctuations of $S_n = X_n^1 + \dots + X_n^n$ are of order $n^{3/4}$ and the limiting law is $C \exp(-\lambda x^4) dx$ for some $C, \lambda > 0$.

For any $n \geq 1$, let us introduce the empirical measure

$$M_n = \frac{1}{n} (\delta_{X_n^1} + \dots + \delta_{X_n^n}).$$

The inequality of theorem 1 is the key ingredient to prove the following theorem:

Theorem 3. *Let ρ be a symmetric probability measure on \mathbb{R} with compact support and such that $\rho(\{0\}) < 1/\sqrt{e}$. Then, under $\tilde{\mu}_{n,\rho}$, the sequence $(M_n)_{n \geq 1}$ converges weakly in probability to ρ , i.e., for any continuous function f from \mathbb{R} to \mathbb{R} , we have*

$$\forall \varepsilon > 0 \quad \lim_{n \rightarrow \infty} \tilde{\mu}_{n,\rho} \left(\left| M_n(f) - \int_{\mathbb{R}} f d\rho \right| \geq \varepsilon \right) = 0.$$

Let us prove this theorem. We suppose that there exists $L > 0$ such that the support of ρ is $[-L, L]$ or $] -L, L[$. We denote by \mathcal{M}_1^L the space of all probability measures on $[-L, L]$ endowed with the topology of weak convergence. Let $\varepsilon > 0$ and let f be a continuous function from \mathbb{R} to \mathbb{R} . The set

$$\mathcal{U}_\varepsilon = \left\{ \mu \in \mathcal{M}_1^L : \left| \int_{\mathbb{R}} f d\mu - \int_{\mathbb{R}} f d\rho \right| < \varepsilon \right\},$$

is open in \mathcal{M}_1^L . Let $n \geq 1$. We denote by $\tilde{\theta}_{n,\rho}$ the law of $(\delta_{Y_1} + \dots + \delta_{Y_n})/n$ when Y_1, \dots, Y_n are n independent random variables with distribution ρ . We have

$$\tilde{\mu}_{n,\rho}(M_n \in \mathcal{U}_\varepsilon^c) = \frac{1}{Z_n} \int_{\mathcal{U}_\varepsilon^c} \exp(n\mathcal{F}(\mu)) \mathbb{1}_{\mu \neq \delta_0} d\tilde{\theta}_{n,\rho}(\mu).$$

The function \mathcal{F} is continuous on $\mathcal{M}_1^L \setminus \{\delta_0\}$. Next, since $\mathcal{F}(\delta_{1/k}) = 1/2$ for any $k \geq 1$, we notice that putting $\mathcal{F}(\delta_0) \geq 1/2$ is necessary to ensure that \mathcal{F} is upper semi-continuous. As a consequence we extend the definition of \mathcal{F} on \mathcal{M}_1^L by putting $\mathcal{F}(\delta_0) = 1/2$. We suppose that $\rho(\{0\}) < 1/\sqrt{e}$ so that

$$\mathcal{F}(\delta_0) = 1/2 < -\ln \rho(\{0\}) = H(\delta_0|\rho).$$

If $\mu \in \mathcal{M}_1^L \setminus \{\delta_0\}$ then theorem 1 implies that $\mathcal{F}(\mu) \leq H(\mu|\rho)$ with equality if and only if $\mu = \rho$. Hence the function $\mathcal{F} - H(\cdot|\rho)$ has a unique maximum on \mathcal{M}_1^L at ρ .

Sanov's theorem (theorem 6.2.10 of [3]) states that $(\tilde{\theta}_{n,\rho})_{n \geq 1}$ satisfies the large deviation principle in \mathcal{M}_1^L with speed n and governed by the good rate function $H(\cdot|\rho)$. As a consequence

$$\liminf_{n \rightarrow +\infty} \frac{1}{n} \ln Z_n \geq \liminf_{n \rightarrow +\infty} \frac{1}{n} \ln \tilde{\theta}_{n,\rho}(\{\delta_0\}^c) \geq - \inf_{\mu \neq \delta_0} H(\mu|\rho) = 0.$$

Since \mathcal{F} is bounded (by 1/2) and is upper semi-continuous on \mathcal{M}_1^L , Varadhan's lemma (see section 4.3 of [3]) implies that

$$\begin{aligned} \limsup_{n \rightarrow +\infty} \frac{1}{n} \ln \tilde{\mu}_{n,\rho}(M_n \in \mathcal{U}_\varepsilon^c) &\leq \limsup_{n \rightarrow +\infty} \frac{1}{n} \ln \int_{\mathcal{U}_\varepsilon^c} e^{n\mathcal{F}(\mu)} d\tilde{\theta}_{n,\rho}(\mu) - \liminf_{n \rightarrow +\infty} \frac{1}{n} \ln Z_n \\ &\leq \sup \{ \mathcal{F}(\mu) - H(\mu|\rho) : \mu \in \mathcal{U}_\varepsilon^c \}. \end{aligned}$$

Since $H(\cdot|\rho)$ is a good rate function, \mathcal{F} is upper semi-continuous and $\mathcal{U}_\varepsilon^c$ is a closed subset of \mathcal{M}_1^L which does not contain ρ , the unique maximum of the function $\mathcal{F} - H(\cdot|\rho)$, we get

$$\sup \{ \mathcal{F}(\mu) - H(\mu|\rho) : \mu \in \mathcal{U}_\varepsilon^c \} < 0.$$

As a consequence, there exists $c_\varepsilon > 0$ and $n_\varepsilon \geq 1$ such that

$$\forall n \geq n_\varepsilon \quad \tilde{\mu}_{n,\rho}(M_n \in \mathcal{U}_\varepsilon^c) \leq \exp(-nc_\varepsilon).$$

This implies the convergence in theorem 3.

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