Lecture 4: The Entropy Methods

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1 Logarithmic Sobolev Inequality

1.1 Bernoulli Logarithmic Sobolev Inequality

- **Remark** (*Setting*)
  Consider a ***uniformly distributed binary vector*** $Z = (Z_1, \ldots, Z_n)$ on the hypercube $\{-1, +1\}^n$. In other words, the components of X are *independent*, *identically distributed* ***random sign (Rademacher) variables*** with $\mathbb{P}\{Z_i = -1\} = \mathbb{P}\{Z_i = +1\} = 1/2$ (i.e. *symmetric Bernoulli random variables*).

  Let $f : \{-1, +1\}^n \to \mathbb{R}$ be a real-valued function on ***binary hypercube***. $X := f(Z)$ is an induced real-valued random variable. Define $\widetilde{Z}^{(i)} = (Z_1, \ldots, Z_{i-1}, Z'_i, Z_{i+1}, \ldots, Z_n)$ be the sample Z with i-th component replaced by an *independent copy* Z'_i. Since $Z, \widetilde{Z}^{(i)} \in \{-1, +1\}^n$, $\widetilde{Z}^{(i)} = (Z_1, \ldots, Z_{i-1}, -Z_i, Z_{i+1}, \ldots, Z_n)$, i.e. *the i-th sign is* ***flipped***. Also denote the i-th *Jackknife sample* as $Z_{(i)} = (Z_1, \ldots, Z_{i-1}, Z_{i+1}, \ldots, Z_n)$ by *leaving out* the i-th component. $\mathbb{E}_{(-i)}[X] := \mathbb{E}\left[X | Z_{(i)}\right]$.

  Denote the i-th component of ***discrete gradient*** of f as

  $$\nabla_i f(z) := \frac{1}{2}\left(f(z) - f(\widetilde{z}^{(i)})\right)$$

  and $\nabla f(z) = (\nabla_1 f(z), \ldots, \nabla_n f(z))$

- **Remark** (***Jackknife Estimate of Variance***)
  Recall that *the* ***Jackknife estimate of variance***

  $$\begin{aligned}\mathcal{E}(f) &:= \mathbb{E}\left[\sum_{i=1}^{n}\left(f(Z) - \mathbb{E}_{(-i)}\left[f(\widetilde{Z}^{(i)})\right]\right)^2\right] \\ &= \frac{1}{2}\mathbb{E}\left[\sum_{i=1}^{n}\left(f(Z) - f(\widetilde{Z}^{(i)})\right)^2\right].\end{aligned}$$

  Using the notation of discrete gradient of f, we see that

  $$\mathcal{E}(f) := 2\mathbb{E}\left[\|\nabla f(Z)\|_2^2\right]$$

- **Remark** (***Entropy Functional***)
  Recall that the entropy functional for f is defined as

  $$H_\Phi(f(Z)) = \mathrm{Ent}(f) := \mathbb{E}\left[f(Z)\log f(Z)\right] - \mathbb{E}\left[f(Z)\right]\log\left(\mathbb{E}\left[f(Z)\right]\right).$$

- **Proposition 1.1** *(**Logarithmic Sobolev Inequality for Rademacher Random Variables**). [Boucheron et al., 2013]*
  If $f : \{-1, +1\}^n \to \mathbb{R}$ be an arbitrary real-valued function defined on the n-dimensional ***binary hypercube*** *and assume that Z is* ***uniformly distributed*** *over $\{-1, +1\}^n$. Then*

  $$\begin{aligned} Ent(f^2) &\le \mathcal{E}(f) \qquad (1)\\ \Leftrightarrow Ent(f^2(Z)) &\le 2\mathbb{E}\left[\|\nabla f(Z)\|_2^2\right] \qquad (2)\end{aligned}$$

Proof: The key is to apply the tensorization property of Φ-entropy. Let $X = f(Z)$. By tensorization property,

$$\text{Ent}(X^2) \le \sum_{i=1}^{n} \mathbb{E}\left[\text{Ent}_{(-i)}(X^2)\right]$$

where $\text{Ent}_{(-i)}(X^2) := \mathbb{E}_{(-i)}\left[X^2 \log X^2\right] - \mathbb{E}_{(-i)}\left[X^2\right] \log\left(\mathbb{E}_{(-i)}\left[X^2\right]\right)$.

It thus suffice to show that for all $i = 1\,, \ldots, n$,

$$\text{Ent}_{(-i)}(X^2) \le \frac{1}{2}\mathbb{E}_{(-i)}\left[\left(f(Z) - f(\widetilde{Z}^{(i)})\right)^2\right].$$

Given any fixed realization of $Z_{(-i)}$, $X = f(Z) = \widetilde{f}(Z_i)$ can only takes two different values with equal probability. Call these two values a and b. See that

$$\text{Ent}_{(-i)}(X^2) = \frac{1}{2}a^2 \log a^2 + \frac{1}{2}b^2 \log b^2 - \frac{1}{2}(a^2 + b^2)\log\left(\frac{a^2 + b^2}{2}\right)$$

$$\frac{1}{2}\mathbb{E}_{(-i)}\left[\left(f(Z) - f(\widetilde{Z}^{(i)})\right)^2\right] = \frac{1}{2}\left(a - b\right)^2.$$

Thus we need to show

$$\frac{1}{2}a^2 \log a^2 + \frac{1}{2}b^2 \log b^2 - \frac{1}{2}(a^2 + b^2)\log\left(\frac{a^2 + b^2}{2}\right) \le \frac{1}{2}\left(a - b\right)^2.$$

By symmetry, we may assume that $a \ge b$. Since $(|a| - |b|)^2 \le (a - b)^2$, without loss of generality, we may further assume that $a, b \ge 0$.

Define

$$h(a) := \frac{1}{2}a^2 \log a^2 + \frac{1}{2}b^2 \log b^2 - \frac{1}{2}(a^2 + b^2)\log\left(\frac{a^2 + b^2}{2}\right) - \frac{1}{2}\left(a - b\right)^2$$

for $a \in [b, \infty)$. $h(b) = 0$. It suffice to check that $h'(b) = 0$ and that h is concave on $[b, \infty)$. Note that

$$\begin{aligned} h'(a) &= a \log a^2 + 1 - a \log\left(\frac{a^2 + b^2}{2}\right) - 1 - (a - b) \\ &= a \log \frac{2a^2}{(a^2 + b^2)} - (a - b). \end{aligned}$$

So $h'(b) = 0$. Moreover,

$$h''(a) = \log \frac{2a^2}{(a^2 + b^2)} + 1 - \frac{2a^2}{(a^2 + b^2)} \le 0$$

due to inequality $\log(x) + 1 \le x$. ∎

- **Remark** (***Logarithmic Sobolev Inequality*** $\Rightarrow$ ***Efron-Stein Inequality***). [Boucheron et al., 2013]
Note that for f non-negative,

$$\text{Var}(f(Z)) \le \text{Ent}(f^2(Z)).$$

Thus *logarithmic Sobolev inequality* (1) implies

$$\mathrm{Var}(f(Z)) \le \mathcal{E}(f)$$

which is *the Efron-Stein inequality.*

- **Corollary 1.2** ***(Logarithmic Sobolev Inequality for Asymmetric Bernoulli Random Variables)****. [Boucheron et al., 2013]*
If $f : \{-1,+1\}^n \to \mathbb{R}$ be an arbitrary real-valued function and $Z = (Z_1, \ldots, Z_n) \in \{-1,+1\}^n$ with $p = \mathbb{P}\{Z_i = +1\}$. Then

$$Ent(f^2) \le c(p)\mathbb{E}\left[\|\nabla f(Z)\|_2^2\right] \tag{3}$$

where

$$c(p) = \frac{1}{1-2p}\log\frac{1-p}{p}$$

Note that $\lim_{p\to 1/2} c(p) = 2$.

1.2 Gaussian Logarithmic Sobolev Inequality

- **Proposition 1.3** ***(Gaussian Logarithmic Sobolev Inequality)****. [Boucheron et al., 2013]*
Let $f : \mathbb{R}^n \to \mathbb{R}$ be a ***continuous differentiable*** *function and let $Z = (Z_1, \ldots, Z_n)$ be a vector of n* ***independent standard Gaussian*** *random variables. Then*

$$Ent(f^2(Z)) \le 2\mathbb{E}\left[\|\nabla f(Z)\|_2^2\right]. \tag{4}$$

Proof: We first prove for $n = 1$, where $f : \mathbb{R} \to \mathbb{R}$ is continuous differentiable and Z is standard Gaussian distribution. Without loss of generality, assume that $\mathbb{E}[f'(Z)] < \infty$ since it is trivial when $\mathbb{E}[f'(Z)] = \infty$. By density argument, it suffice to prove the proposition when f is *twice differentiable with bounded support.*

Now let $\epsilon_1, \ldots, \epsilon_n$ be *independent Rademacher random variables* and introduce

$$S_n := \frac{1}{\sqrt{n}}\sum_{j=1}^{n}\epsilon_j.$$

Note that $\epsilon_i \in \{-1,+1\}$ with equal probability, thus

$$\begin{aligned}\mathbb{E}_{(-i)}[S_n] &= \frac{1}{2}\left[\left(\frac{1}{\sqrt{n}}\sum_{j\neq i}\epsilon_j + \frac{1}{\sqrt{n}}\right) + \left(\frac{1}{\sqrt{n}}\sum_{j\neq i}\epsilon_j - \frac{1}{\sqrt{n}}\right)\right] \\ &= \frac{1}{2}\left[\left(S_n + \frac{1-\epsilon_i}{\sqrt{n}}\right) + \left(S_n - \frac{1+\epsilon_i}{\sqrt{n}}\right)\right].\end{aligned}$$

In the proof of Gaussian Poincaré inequality, we show that by *central limit theorem*,

$$\limsup_{n\to\infty}\mathbb{E}\left[\sum_{i=1}^{n}\left|f(S_n) - f\left(S_n - \frac{2\epsilon_i}{\sqrt{n}}\right)\right|^2\right] = 4\mathbb{E}\left[(f'(Z))^2\right].$$

On the other hands, for any *continuous uniformly bounded function* f, by *central limit theorem*,

$$\lim_{n\to\infty} \mathrm{Ent}\left(f^2(S_n)\right) = \mathrm{Ent}(f^2(Z))$$

The proof is then completed by invoking *the logarithmic Sobolev inequality* for *Rademacher random variables*

$$\begin{aligned}
\mathrm{Ent}\left(f^2(S_n)\right) &\le \frac{1}{2}\mathbb{E}\left[\sum_{i=1}^{n}\left|f\left(S_n\right) - f\left(S_n - \frac{2\epsilon_i}{\sqrt{n}}\right)\right|^2\right] \\
\Rightarrow \lim_{n\to\infty} \mathrm{Ent}\left(f^2(S_n)\right) &\le \frac{1}{2}\lim_{n\to\infty} \mathbb{E}\left[\sum_{i=1}^{n}\left|f\left(S_n\right) - f\left(S_n - \frac{2\epsilon_i}{\sqrt{n}}\right)\right|^2\right] \\
\Rightarrow \mathrm{Ent}(f^2(Z)) &\le 2\mathbb{E}\left[(f'(Z))^2\right].
\end{aligned}$$

The extension of the result to dimension $n \ge 1$ follows easily from *the sub-additivity of entropy* which states that

$$\mathrm{Ent}(f^2) \le \sum_{i=1}^{n} \mathbb{E}\left[\mathbb{E}_{(-i)}\left[f^2(Z)\log f^2(Z)\right] - \mathbb{E}_{(-i)}\left[f^2(Z)\right]\log \mathbb{E}_{(-i)}\left[f^2(Z)\right]\right]$$

where $\mathbb{E}_{(-i)}\left[\cdot\right]$ denotes the integration with respect to i-th variable Z_i only. Thus by induction, for all i

$$\mathbb{E}_{(-i)}\left[f^2(Z)\log f^2(Z)\right] - \mathbb{E}_{(-i)}\left[f^2(Z)\right]\log \mathbb{E}_{(-i)}\left[f^2(Z)\right] \le 2\mathbb{E}_{(-i)}\left[(\partial_i f(Z))^2\right].$$

Thus

$$\mathrm{Ent}(f^2) \le 2\mathbb{E}\left[\mathbb{E}_{(-i)}\left[\sum_{i=1}^{n}(\partial_i f(Z))^2\right]\right] = 2\mathbb{E}\left[\|\nabla f(Z)\|_2^2\right]. \qquad \blacksquare$$

- **Remark** (***Dimension Free Property***).
  The Gaussian logarithmic Sobolev inequality has a constant $C = 2$ that is ***independent of dimension*** n:

  $$\mathbb{E}_{\mu}\left[f^2\right] \le 2\mathbb{E}_{\mu}\left[\|\nabla f\|_2^2\right].$$

  This *dimension-free property* is related to *the* ***concentration*** *of* ***Gaussian measure*** μ. As a consequence, this inequality can be extended to functions of *Gaussian measure* on ***infinite dimensional space***, such as Gibbs measure, *Gaussian process* etc.

- **Remark** (***Equivalent Form of Gaussian Logarithmic Sobolev Inequality***)
  Assume $f : \mathbb{R}^n \to (0, \infty)$ and $\int_{\mathbb{R}^n} f d\mu = 1$ under Gaussian measure μ. Substituting $f \to \sqrt{f}$, *the logarithmic Sobolev inequality* becomes

  $$\mathrm{Ent}_{\mu}(f) = \int f \log f d\mu \le \frac{1}{2}\int \frac{\|\nabla f\|_2^2}{f} d\mu \tag{5}$$

- **Remark** (***Gaussian Logarithmic Sobolev Inequality*** $\Rightarrow$ ***Gaussian Poincaré Inequality***). [Boucheron et al., 2013]
Recall that *the Gaussian Poincaré inequality*

$$\mathrm{Var}(f(Z)) \le \mathbb{E}\left[\|\nabla f(Z)\|_2^2\right]$$

Since

$$(1+t)\log(1+t) = t + \frac{t^2}{2} + o(t^2)$$

as $t \to 0$, we can get for Gaussian measures,

$$\mathrm{Ent}_\mu(1+\epsilon h) = \frac{\epsilon^2}{2}\mathrm{Var}_\mu(h) + o(\epsilon^2).$$

Similarly,

$$\int \frac{\|\nabla(1+\epsilon h)\|_2^2}{1+\epsilon h} d\mu = \epsilon^2 \int \|\nabla h\|_2^2 \, d\mu + o(\epsilon^2).$$

Thus from *the Gaussian logarithmic Sobolev inequality*,

$$\begin{aligned} \mathrm{Ent}_\mu(1+\epsilon h) &\le \frac{1}{2}\int \frac{\|\nabla(1+\epsilon h)\|_2^2}{1+\epsilon h} d\mu \\ \Leftrightarrow \frac{\epsilon^2}{2}\mathrm{Var}_\mu(h) + o(\epsilon^2) &\le \frac{\epsilon^2}{2}\int \|\nabla h\|_2^2 \, d\mu + o(\epsilon^2) \\ \Leftrightarrow \mathrm{Var}(f(Z)) &\le \mathbb{E}\left[\|\nabla f(Z)\|_2^2\right] \qquad \text{as } \epsilon \to 0. \end{aligned}$$

Thus *the Gaussian logarithmic Sobolev inequality* implies *the Gaussian Poincaré inequality.*

1.3 Information Theory Interpretation

- **Remark** (***Information Interpretation of Gaussian Logarithmic Sobolev Inequality***)
Let ν, μ be two *probability measures* on $(\mathcal{X}^n, \mathscr{F})$, $\mu = \mu_1 \otimes \ldots \otimes \mu_n$ and $\nu \ll \mu$. Define $f := \frac{d\nu}{d\mu}$ be *the Radon-Nikodym derivative* of ν with respect to μ (i.e f is the *probability density function* of ν with respect to μ). Then the entropy becomes ***the relative entropy***

$$\mathrm{Ent}_\mu(f) := \mathbb{E}_\mu[f \log f] = \mathbb{KL}(\nu \,\|\, \mu)$$

since $\mathbb{E}_\mu[f] = \int_{\mathcal{X}^n} f d\mu = 1$.

On the other hand, ***the (relative) Fisher information*** is defined as

$$\begin{aligned} I(\nu \,\|\, \mu) &:= \mathbb{E}_\nu\left[\|\nabla \log f\|_2^2\right] \\ &= \int \left\|\frac{\nabla f}{f}\right\|_2^2 d\nu = \int \frac{\|\nabla f\|_2^2}{f^2} d\nu \\ &= \int \frac{\|\nabla f\|_2^2}{f} d\mu \end{aligned}$$

Thus ***the information interpretation*** of *the Gaussian logarithmic Sobolev inequality* is

$$\mathbb{KL}\left(\nu \,\|\, \mu\right) \le \frac{1}{2} I(\nu \,\|\, \mu) \tag{6}$$

where μ is a *Gaussian measure* and $\nu \ll \mu$ with density function f. Note that *the Fisher information metric is* ***the Riemannian metric*** *induced by the relative entropy.*

1.4 Logarithmic Sobolev Inequality for General Probability Measures

- From functional analysis, we have *the Sobolev inequality*,

  Remark (***The Sobolev Inequality***) [Evans, 2010]
  The Sobolev inequality states for smooth function $f : \mathbb{R}^n \to \mathbb{R}$ in *Sobolev space* where $n \ge 3$ and $p = \frac{2n}{n-2} > 2$

  $$\|f\|_p^2 \le C_n \int_{\mathbb{R}^n} |\nabla f|^2 \, dx.$$

  The inequality is sharp when the constant

  $$C_n := \frac{1}{\pi n(n-2)} \left(\frac{\Gamma(n)}{\Gamma(n/2)} \right)^{2/n}$$

- **Proposition 1.4** ***(Euclidean Logarithmic Sobolev Inequality).***
  Let $f : \mathbb{R}^n \to \mathbb{R}$ be a smooth function and m be Lebesgue measure on $\mathbb{R}^n$, then

  $$\begin{aligned} Ent_m(f^2) &\le \frac{n}{2} \log\left(\frac{2}{n\pi e} \mathbb{E}_m \left[\|\nabla f\|_2^2 \right] \right) \qquad (7)\\ \Leftrightarrow \int f^2 \log\left(\frac{f^2}{\int f^2 dx} \right) dx &\le \frac{n}{2} \log\left(\frac{2}{n\pi e} \int |\nabla f|^2 \, dx \right) \end{aligned}$$

- **Definition** (***Logarithmic Sobolev Inequality for General Probability Measure***).
  A probability measure μ on $\mathbb{R}^n$ is said to satisfy the ***logarithmic Sobolev inequality*** for some constant $C > 0$ if for any smooth function f

  $$\mathrm{Ent}_\mu(f^2) \le C \, \mathbb{E}_\mu \left[\|\nabla f\|_2^2 \right] \tag{8}$$

  holds for any ***continuous differentiable*** function $f : \mathbb{R}^n \to \mathbb{R}$. The left-hand side is called ***the entropy functional***, which is defined as

  $$\begin{aligned} \mathrm{Ent}(f^2) &:= \mathbb{E}_\mu \left[f^2 \log f^2 \right] - \mathbb{E}_\mu \left[f^2 \right] \log \mathbb{E}_\mu \left[f^2 \right] \\ &= \int f^2 \log\left(\frac{f^2}{\int f^2 d\mu} \right) d\mu. \end{aligned}$$

  The right-hand side is defined as

  $$\mathbb{E}_\mu \left[\|\nabla f\|_2^2 \right] = \int \|\nabla f\|_2^2 \, d\mu.$$

  Thus we can rewrite *the logarithmic Sobolev inequality* in *functional form*

  $$\int f^2 \log\left(\frac{f^2}{\int f^2 d\mu} \right) d\mu \le C \int \|\nabla f\|_2^2 \, d\mu \tag{9}$$

- **Remark** (***Logarithmic Sobolev Inequality***)
  For non-negative function f, we can replace $f \to \sqrt{f}$, so that *the logarithmic Sobolev inequality* becomes

$$\mathrm{Ent}_{\mu}(f) \le C \int \frac{\|\nabla f\|_2^2}{f} d\mu \tag{10}$$

- **Remark** (***Modified Logarithmic Sobolev Inequality via Convex Cost and Duality***)
  For some ***convex non-negative cost*** $c : \mathbb{R}^n \to \mathbb{R}_+$, ***the convex conjugate*** of c (Legendre transform of c) is defined as

$$c^*(x) := \sup_{y} \{\langle x\,,\, y\rangle - c(y)\}$$

  Then we can obtain ***the modified logarithmic Sobolev inequality***

$$\mathrm{Ent}_{\mu}(f) \le \int f^2\, c^* \left(\frac{\nabla f}{f}\right) d\mu \tag{11}$$

1.5 Applications

1.5.1 Lipschitz Functions of Gaussian Variables

1.5.2 Supremum of Gaussian Process

1.5.3 Hypercontractivity for Boolean Polynomials

1.5.4 Gaussian Hypercontractivity

2 The Entropy Methods

2.1 Herbst's Argument

- **Remark** Recall that the Φ-entropy for $\Phi(x) = x\log(x)$ as

$$H_{\Phi}(X) = \mathrm{Ent}(X) := \mathbb{E}\left[X \log X\right] - \mathbb{E}\left[X\right] \log\left(\mathbb{E}\left[X\right]\right).$$

  The variational formulation of $H_{\Phi}(X)$ is

$$\mathrm{Ent}(X) = \sup_{T} \{X\left(\log(T) - \log(\mathbb{E}\left[T\right])\right)\}$$

- **Remark** (***Tensorization Property of Entropy Functional***)
  Let $\mu = \mu_1 \otimes \ldots \otimes \mu_n$ be the probability distribution for $Z = (Z_1\,, \ldots, Z_n)$ on $(\mathcal{X}^n, \mathscr{F})$. For any measurable function $f : \mathcal{X}^n \to \mathbb{R}$, let $X = f(Z_1\,, \ldots, Z_n)$ so that $\mathbb{E}\left[X \log X\right] < \infty$. The *sub-additivity of entropy function (i.e. the tensorization property)* states that

$$\mathrm{Ent}_{\mu_1 \otimes \ldots \otimes \mu_n}(f) \le \mathbb{E}_{\mu_1 \otimes \ldots \otimes \mu_n}\left[\sum_{i=1}^{n} \mathrm{Ent}_{\mu_i}(f)\right]$$

  where the subscript μ_i indicates that the integration concerns the i-th variable only.

- **Remark** (***Entropy Functional for Moment Generating Function***)
Let $X = e^{\lambda Z}$ where Z is a random variable. The entropy function of X becomes

$$\mathrm{Ent}(e^{\lambda Z}) = \mathbb{E}\left[\lambda Z e^{\lambda Z}\right] - \mathbb{E}\left[e^{\lambda Z}\right]\log\left(\mathbb{E}\left[e^{\lambda Z}\right]\right)$$

Denote $\psi_{Z-\mathbb{E}[Z]}(\lambda) := \log \mathbb{E}\left[e^{\lambda(Z-\mathbb{E}[Z])}\right]$. Then

$$\begin{aligned}
\psi'_{Z-\mathbb{E}[Z]}(\lambda) &= \frac{d}{d\lambda}\log \mathbb{E}\left[e^{\lambda(Z-\mathbb{E}[Z])}\right] \\
&= \frac{1}{\mathbb{E}\left[e^{\lambda(Z-\mathbb{E}[Z])}\right]}\mathbb{E}\left[\left(Z-\mathbb{E}\left[Z\right]\right)e^{\lambda(Z-\mathbb{E}[Z])}\right] \\
&= \frac{1}{\mathbb{E}\left[e^{\lambda Z}\right]}e^{\lambda\mathbb{E}[Z]}\mathbb{E}\left[\left(Z-\mathbb{E}\left[Z\right]\right)e^{\lambda(Z-\mathbb{E}[Z])}\right] \\
&= \frac{1}{\mathbb{E}\left[e^{\lambda Z}\right]}\mathbb{E}\left[\left(Z-\mathbb{E}\left[Z\right]\right)e^{\lambda Z}\right] \\
&= \frac{1}{\mathbb{E}\left[e^{\lambda Z}\right]}\mathbb{E}\left[Z e^{\lambda Z}\right] - \mathbb{E}\left[Z\right] \\
\Rightarrow \lambda\, \psi'_{Z-\mathbb{E}[Z]}(\lambda) &= \frac{1}{\mathbb{E}\left[e^{\lambda Z}\right]}\left(\mathbb{E}\left[\lambda Z e^{\lambda Z}\right] - \mathbb{E}\left[\lambda Z\right]\mathbb{E}\left[e^{\lambda Z}\right]\right) \\
\Rightarrow \lambda\, \psi'_{Z-\mathbb{E}[Z]}(\lambda) - \psi_{Z-\mathbb{E}[Z]}(\lambda) &= \frac{1}{\mathbb{E}\left[e^{\lambda Z}\right]}\left\{\mathbb{E}\left[\lambda Z e^{\lambda Z}\right] - \mathbb{E}\left[\lambda Z\right]\mathbb{E}\left[e^{\lambda Z}\right] - \mathbb{E}\left[e^{\lambda Z}\right]\log\mathbb{E}\left[e^{\lambda(Z-\mathbb{E}[Z])}\right]\right\} \\
&= \frac{1}{\mathbb{E}\left[e^{\lambda Z}\right]}\left\{\mathbb{E}\left[\lambda Z e^{\lambda Z}\right] - \mathbb{E}\left[\lambda Z\right]\mathbb{E}\left[e^{\lambda Z}\right]\right. \\
&\quad \left. + \mathbb{E}\left[e^{\lambda Z}\right]\mathbb{E}\left[\lambda Z\right] - \mathbb{E}\left[e^{\lambda Z}\right]\log\mathbb{E}\left[e^{\lambda Z}\right]\right\} \\
&= \frac{1}{\mathbb{E}\left[e^{\lambda Z}\right]}\left\{\mathbb{E}\left[\lambda Z e^{\lambda Z}\right] - \mathbb{E}\left[e^{\lambda Z}\right]\log\mathbb{E}\left[e^{\lambda Z}\right]\right\} \\
&= \frac{\mathrm{Ent}(e^{\lambda Z})}{\mathbb{E}\left[e^{\lambda Z}\right]}
\end{aligned}$$

Thus we have

$$\frac{\mathrm{Ent}(e^{\lambda Z})}{\mathbb{E}\left[e^{\lambda Z}\right]} = \lambda\, \psi'_{Z-\mathbb{E}[Z]}(\lambda) - \psi_{Z-\mathbb{E}[Z]}(\lambda). \tag{12}$$

Our strategy is based on using (12) *the sub-additivity of entropy* and then univariate calculus to derive ***upper bounds*** *for the* ***derivative*** *of* $\psi(\lambda)$. By solving the obtained ***differential inequality***, we obtain tail bounds via *Chernoff's bounding*.

- **Proposition 2.1** ***(Herbst's Argument)*** *[Boucheron et al., 2013, Wainwright, 2019]*
Let Z be an integrable random variable such that for some $\nu > 0$, we have, for every $\lambda > 0$,

$$\frac{Ent(e^{\lambda Z})}{\mathbb{E}\left[e^{\lambda Z}\right]} \le \frac{\nu\lambda^2}{2} \tag{13}$$

Then, for every $\lambda > 0$, the logarithmic moment generating function of centered random variable $(Z - \mathbb{E}\left[Z\right])$ satisfies

$$\psi_{Z-\mathbb{E}[Z]}(\lambda) := \log\mathbb{E}\left[e^{\lambda(Z-\mathbb{E}[Z])}\right] \le \frac{\nu\lambda^2}{2}.$$

Proof: The condition of the proposition means, via (12), that

$$\lambda\, \psi'_{Z-\mathbb{E}[Z]}(\lambda) - \psi_{Z-\mathbb{E}[Z]}(\lambda) \le \frac{\nu\lambda^2}{2},$$

or equivalently,

$$\frac{1}{\lambda}\psi'_{Z-\mathbb{E}[Z]}(\lambda) - \frac{1}{\lambda^2}\psi_{Z-\mathbb{E}[Z]}(\lambda) \le \frac{\nu}{2}.$$

Setting $G(\lambda) = \lambda^{-1}\psi_{Z-\mathbb{E}[Z]}(\lambda)$, we see that the differential inequality becomes

$$G'(\lambda) \le \frac{\nu}{2}.$$

Since $G(\lambda) \to 0$ as $\lambda \to 0$, which implies that

$$G(\lambda) \le \frac{\nu\lambda}{2},$$

and the result follows. ∎

2.2 Bounded Difference Inequality

2.3 Modified Logarithmic Sobolev Inequalities

- **Proposition 2.2** ***(A Modified Logarithmic Sobolev Inequalities for Moment Generating Function)*** *[Boucheron et al., 2013]*
  Consider independent random variables $Z_1, \ldots, Z_n$ taking values in $\mathcal{X}$, a real-valued function $f : \mathcal{X}^n \to \mathbb{R}$ and the random variable $X = f(Z_1, \ldots, Z_n)$. Also denote $Z_{(-i)} = (Z_1, \ldots, Z_{i-1}, Z_{i+1}, \ldots, Z_n)$ and $X_{(-i)} = f_i(Z_{(-i)})$ where $f_i : \mathcal{X}^{n-1} \to \mathbb{R}$ is an arbitrary function. Let $\phi(x) = e^x - x - 1$. Then for all $\lambda \in \mathbb{R}$,

  $$\lambda\mathbb{E}\left[Xe^{\lambda X}\right] - \mathbb{E}\left[e^{\lambda X}\right]\log\mathbb{E}\left[e^{\lambda X}\right] \le \sum_{i=1}^{n}\mathbb{E}\left[e^{\lambda X}\phi(-\lambda(X - X_{(-i)}))\right] \tag{14}$$

  Proof:

- **Proposition 2.3** ***(Symmetrized Modified Logarithmic Sobolev Inequalities)*** *[Boucheron et al., 2013]*
  Consider independent random variables $Z_1, \ldots, Z_n$ taking values in $\mathcal{X}$, a real-valued function $f : \mathcal{X}^n \to \mathbb{R}$ and the random variable $X = f(Z_1, \ldots, Z_n)$. Also denote $\widetilde{X}^{(i)} = f(Z_1, \ldots, Z_{i-1}, Z_i', Z_{i+1}, \ldots, Z_n)$. Let $\phi(x) = e^x - x - 1$. Then for all $\lambda \in \mathbb{R}$,

  $$\lambda\mathbb{E}\left[Xe^{\lambda X}\right] - \mathbb{E}\left[e^{\lambda X}\right]\log\mathbb{E}\left[e^{\lambda X}\right] \le \sum_{i=1}^{n}\mathbb{E}\left[e^{\lambda X}\phi(-\lambda(X - \widetilde{X}^{(i)}))\right] \tag{15}$$

  Moreover, denoting $\tau(x) = x(e^x - 1)$, for all $\lambda \in \mathbb{R}$,

  $$\lambda\mathbb{E}\left[Xe^{\lambda X}\right] - \mathbb{E}\left[e^{\lambda X}\right]\log\mathbb{E}\left[e^{\lambda X}\right] \le \sum_{i=1}^{n}\mathbb{E}\left[e^{\lambda X}\tau(-\lambda(X - \widetilde{X}^{(i)})_+)\right],$$

  $$\lambda\mathbb{E}\left[Xe^{\lambda X}\right] - \mathbb{E}\left[e^{\lambda X}\right]\log\mathbb{E}\left[e^{\lambda X}\right] \le \sum_{i=1}^{n}\mathbb{E}\left[e^{\lambda X}\tau(\lambda(\widetilde{X}^{(i)} - X)_-)\right].$$

2.4 Poisson Logarithmic Sobolev Inequality

- **Proposition 2.4** *(**Modified Logarithmic Sobolev Inequality for Bernoulli Random Variable**). [Boucheron et al., 2013]*
  *Let $f : \{0,1\} \to (0,\infty)$ be a **non-negative** real-valued function defined on the binary set $\{0,1\}$. Define **the discrete derivative** of f at $x \in \{0,1\}$ by*

$$\nabla f := f(1-x) - f(x).$$

  Let X be a Bernoulli random variable with parameter $p \in (0,1)$ (i.e. $\mathbb{P}\{X = 1\} = p$). Then

$$\mathit{Ent}(f(X)) \le (p(1-p))\mathbb{E}\left[\nabla f(X) \nabla \log f(X)\right]. \tag{16}$$

  and

$$\mathit{Ent}(f(X)) \le (p(1-p))\mathbb{E}\left[\frac{|\nabla f(X)|^2}{f(X)}\right]. \tag{17}$$

- **Proposition 2.5** *(**Poisson Logarithmic Sobolev Inequality**). [Boucheron et al., 2013]*
  *Let $f : \mathbb{N} \to (0,\infty)$ be a **non-negative** real-valued function defined on the set of non-negative integers $\mathbb{N}$. Define **the discrete derivative** of f at $x \in \mathbb{N}$ by*

$$\nabla f := f(x+1) - f(x).$$

  Let X be a Poisson random variable. Then

$$\mathit{Ent}(f(X)) \le (\mathbb{E}\left[X\right])\mathbb{E}\left[\nabla f(X) \nabla \log f(X)\right]. \tag{18}$$

  and

$$\mathit{Ent}(f(X)) \le (\mathbb{E}\left[X\right])\mathbb{E}\left[\frac{|\nabla f(X)|^2}{f(X)}\right]. \tag{19}$$

2.5 Applications

2.5.1 The Johnson-Lindenstrauss Lemma

2.5.2 Concentration of Convex Lipschitz Functions

2.5.3 Exponential Tail Bounds for Self-Bounding Functions

References

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