Lecture 5: Concentration of Measure and Isoperimetry

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Contents

1 The Classic Isoperimetry Inequalities

1.1 Brunn-Minkowski Inequality

- **Definition** (***Minkowski Sum of Sets***)
  Consider sets $A, B \subseteq \mathbb{R}^n$ and define ***the Minkowski sum*** of A and B as the set of all vectors in $\mathbb{R}^n$ formed by sums of elements of A and B:

$$A + B := \{x + y : x \in A, y \in B\}$$

  Similarly, for $c \in \mathbb{R}$, let $cA = \{cx : x \in A\}$. Denote by $\mathrm{Vol}(A)$ the ***Lebesgue measure*** of a *(measurable) set* $A \subset \mathbb{R}^n$.

- **Theorem 1.1** *(**Brunn-Minkowski Inequality**) [Boucheron et al., 2013, Vershynin, 2018, Wainwright, 2019]*
  *Let $A, B \subset \mathbb{R}^n$ be **non-empty compact sets**. Then for all $\lambda \in [0, 1]$,*

$$Vol\,(\lambda A + (1-\lambda)B)^{\frac{1}{n}} \geq \lambda\, Vol(A)^{\frac{1}{n}} + (1-\lambda)\, Vol(B)^{\frac{1}{n}}. \tag{1}$$

  Note: a convex body in $\mathbb{R}^n$ is closed and compact set.

  Proof: (***Part 1,*** $n = 1$)
  Note that if $A \subset \mathbb{R}$, and $c \geq 0$ then $\mathrm{Vol}(cA) = c\mathrm{Vol}(A)$. Thus it suffice to prove

$$\mathrm{Vol}\,(A + B) \geq \mathrm{Vol}(A) + \mathrm{Vol}(B).$$

  To see this, observe that none of the three volumes involved changes if the sets A and B are ***translated*** arbitrarily. Since A, B are compact subsets in $\mathbb{R}$, it is closed and bounded. Let $a = \max\{a' : a' \in A\}$ and $b = \min\{b' : b' \in B\}$. Let $A' = A + \{-a\}$ and $B' = B + \{-b\}$ so that $A' \subset (-\infty, 0]$ and $B' \subset [0, +\infty)$. Also $\mathrm{Vol}(A') = \mathrm{Vol}(A)$ and $\mathrm{Vol}(B') = \mathrm{Vol}(B)$. However,

$$\begin{aligned} A' \cup B' &\subset A' + B' \\ \Rightarrow \mathrm{Vol}(A') + \mathrm{Vol}(B') = \mathrm{Vol}(A' \cup B') &\leq \mathrm{Vol}(A' + B') \end{aligned}$$

  This prove the 1-dimensional case for *the Brunn-Minkowski inequality.* ∎

  To prove $n > 1$ case, we need the following inequalities:

- **Theorem 1.2** *(**The Prékopa-Leindler Inequality**). [Boucheron et al., 2013, Wainwright, 2019]*
  *Let $\lambda \in (0, 1)$, and let $f, g, h : \mathbb{R}^n \to [0, \infty)$ be **non-negative measurable functions** such that for all $x, y \in \mathbb{R}^n$,*

$$h\,(\lambda x + (1-\lambda)y) \geq f(x)^{\lambda} g(y)^{1-\lambda}.$$

  Then

$$\int_{\mathbb{R}^n} h(x)dx \geq \left(\int_{\mathbb{R}^n} f(x)dx\right)^{\lambda} \left(\int_{\mathbb{R}^n} g(x)dx\right)^{1-\lambda}. \tag{2}$$

  Proof: The proof goes by induction with respect to the dimension n.

1. ($n = 1$ ***case***). Consider measurable non-negative functions f, g, h satisfying the condition of the theorem. By *the monotone convergence theorem*, it suffices to prove the statement for ***bounded functions*** f and g. Without loss of generality, assume that $\sup_{x\in\mathbb{R}^n} f(x) = \sup_{x\in\mathbb{R}^n} g(x) = 1$. Then

$$\int_{\mathbb{R}} f(x)dx = \int_0^1 \mathrm{Vol}\,\{x : f(x) \geq t\}\, dt$$
$$\int_{\mathbb{R}} g(x)dx = \int_0^1 \mathrm{Vol}\,\{x : g(x) \geq t\}\, dt.$$

For any fixed $t \in [0, 1]$, if $f(x) \geq t$ and $g(y) \geq t$, then by the hypothesis of the theorem, $h\,(\lambda x + (1-\lambda)y) \geq t$. This implication may be re-written as

$$\lambda\,\{x : f(x) \geq t\} + (1-\lambda)\,\{x : g(x) \geq t\} \subset \{x : h(x) \geq t\}\,.$$

Thus

$$\begin{aligned}
\int_{\mathbb{R}} h(x)dx &= \int_0^\infty \mathrm{Vol}\,\{x : h(x) \geq t\}\, dt \\
&\geq \int_0^1 \mathrm{Vol}\,\{x : h(x) \geq t\}\, dt \\
&\geq \int_0^1 \mathrm{Vol}\,(\lambda\,\{x : f(x) \geq t\}) + \mathrm{Vol}\,((1-\lambda)\,\{x : g(x) \geq t\})\, dt \\
&\text{(by 1-dimensional } \textit{Brunn-Minkowski inequality}) \\
&\geq \lambda \int_0^1 \mathrm{Vol}\,(\{x : f(x) \geq t\})\, dt + (1-\lambda) \int_0^1 \mathrm{Vol}\,(\{x : g(x) \geq t\})\, dt \\
&= \lambda \int_{\mathbb{R}} f(x)dx + (1-\lambda) \int_{\mathbb{R}} g(x)dx \\
&\geq \left(\int_{\mathbb{R}} f(x)dx\right)^{\lambda} \left(\int_{\mathbb{R}} g(x)dx\right)^{1-\lambda} \quad \text{(by the } \textit{arithmetic-geometric mean inequality})
\end{aligned}$$

2. For the induction step, assume that the theorem holds for all dimensions $1, \ldots, n-1$ and let $f, g, h : \mathbb{R}^n \to [0, \infty)$, $\lambda \in (0, 1)$ be such that they satisfy the assumption of the theorem. Now let $x, y \in \mathbb{R}^{n-1}$ and $a, b \in \mathbb{R}$. Then

$$h\,(\lambda\,(x, a) + (1-\lambda)\,(y, b)) \geq f\,((x, a))^{\lambda}\, g((y, b))^{1-\lambda},$$

so by the inductive hypothesis

$$\int_{\mathbb{R}^{n-1}} h\,((x, \lambda a + (1-\lambda)b))\, dx \geq \left(\int_{\mathbb{R}^{n-1}} f\,((x, a))\, dx\right)^{\lambda} \left(\int_{\mathbb{R}^{n-1}} g((x, b))dx\right)^{1-\lambda}$$

In other words, introducing

$$F(a) := \int_{\mathbb{R}^{n-1}} f\,((x, a))\, dx, \quad G(b) := \int_{\mathbb{R}^{n-1}} g((x, b))dx$$
$$H((\lambda a + (1-\lambda)b)) := \int_{\mathbb{R}^{n-1}} h\,((x, \lambda a + (1-\lambda)b))\, dx.$$

We have

$$H((\lambda a+(1-\lambda)b)) \geq (F(a))^{\lambda}\,(G(b))^{1-\lambda},$$

so by *Fubini's theorem* and the one-dimensional inequality, we have

$$\begin{aligned}\int_{\mathbb{R}^n} h(x)dx = \int_{\mathbb{R}} H(a)da &\geq \left(\int_{\mathbb{R}} F(a)da\right)^{\lambda}\left(\int_{\mathbb{R}} G(a)da\right)^{1-\lambda} \\ &= \left(\int_{\mathbb{R}^n} f(x)dx\right)^{\lambda}\left(\int_{\mathbb{R}^n} g(x)dx\right)^{1-\lambda}. \quad \blacksquare\end{aligned}$$

- **Corollary 1.3** *(**Weaker Brunn-Minkowski Inequality**) [Boucheron et al., 2013, Wainwright, 2019]*
  *Let $A, B \subset \mathbb{R}^n$ be **non-empty compact sets**. Then for all $\lambda \in [0,1]$,*

  $$Vol(\lambda A+(1-\lambda)B) \geq Vol(A)^{\lambda}\,Vol(B)^{1-\lambda}. \tag{3}$$

  Proof: We apply *the Prékopa-Leindler inequality* with $f(x)=\mathbb{1}\{x\in A\}$, $g(x)=\mathbb{1}\{x\in B\}$ and $h(x)=\mathbb{1}\{x\in \lambda A+(1-\lambda)B\}$. We see that

  $$h(\lambda x+(1-\lambda)y)=\mathbb{1}\{\lambda x+(1-\lambda)y\in\lambda A+(1-\lambda)B\}\geq \mathbb{1}\{x\in A, y\in B\}=f(x)^{\lambda}g(y)^{1-\lambda}.$$

  Thus the hypothesis of *the Prékopa-Leindler inequality* holds. $\blacksquare$

- **Proof:** ($n>1$ ***case for Brunn-Minkowski Inequality***). First observe that it suffices to prove that for all *nonempty compact sets* A and B,

  $$\mathrm{Vol}\,(A+B)^{\frac{1}{n}} \geq \mathrm{Vol}(A)^{\frac{1}{n}}+\mathrm{Vol}(B)^{\frac{1}{n}}$$

  since $\mathrm{Vol}\,(cA)^{1/n} = c\mathrm{Vol}\,(A)^{1/n}$ for any $c\in\mathbb{R}$ and $A\subset\mathbb{R}^n$. Also notice that we may assume that $\mathrm{Vol}(A), \mathrm{Vol}(B)>0$ because otherwise the inequality holds trivially. Defining $A'=\mathrm{Vol}(A)^{-\frac{1}{n}}A$ and $B'=\mathrm{Vol}(B)^{-\frac{1}{n}}B$, we have $\mathrm{Vol}(A')=\mathrm{Vol}(B')=1$. By *weaker Brunn-Minkowski inequality*, for $\lambda\in(0,1)$,

  $$\mathrm{Vol}\left(\lambda A'+(1-\lambda)B'\right)\geq 1.$$

  Finally, we apply this *inequality* with the choice

  $$\lambda=\frac{\mathrm{Vol}(A)^{\frac{1}{n}}}{\mathrm{Vol}(A)^{\frac{1}{n}}+\mathrm{Vol}(B)^{\frac{1}{n}}}$$

  obtaining

  $$\begin{aligned}\mathrm{Vol}\left(\frac{\mathrm{Vol}(A)^{\frac{1}{n}}A'}{\mathrm{Vol}(A)^{\frac{1}{n}}+\mathrm{Vol}(B)^{\frac{1}{n}}}+\frac{\mathrm{Vol}(B)^{\frac{1}{n}}B'}{\mathrm{Vol}(A)^{\frac{1}{n}}+\mathrm{Vol}(B)^{\frac{1}{n}}}\right) &\geq 1 \\ \Rightarrow \mathrm{Vol}\left(\frac{A}{\mathrm{Vol}(A)^{\frac{1}{n}}+\mathrm{Vol}(B)^{\frac{1}{n}}}+\frac{B}{\mathrm{Vol}(A)^{\frac{1}{n}}+\mathrm{Vol}(B)^{\frac{1}{n}}}\right) &\geq 1 \\ \Rightarrow \mathrm{Vol}\left(\frac{A+B}{\mathrm{Vol}(A)^{\frac{1}{n}}+\mathrm{Vol}(B)^{\frac{1}{n}}}\right) &\geq 1 \\ \Rightarrow \frac{\mathrm{Vol}(A+B)}{\left(\mathrm{Vol}(A)^{\frac{1}{n}}+\mathrm{Vol}(B)^{\frac{1}{n}}\right)^{n}} &\geq 1\end{aligned}$$

  which proves the theorem. $\blacksquare$

Figure 5.1 Isoperimetric inequality in $\mathbb{R}^n$ states that among all sets A of given volume, the Euclidean balls minimize the volume of the ε-neighborhood A_ε.

Figure 1: Isoperimetry in $\mathbb{R}^n$ [Vershynin, 2018]

1.2 The Blowup of Sets and Classical Isoperimetry Theorem

- **Definition** (***Blowup of Sets***)
  For any $t > 0$, and any (measurable) sets $A \subset \mathbb{R}^n$, ***the t-blowup*** *of* A is defined by
  $$A_t := \{x \in \mathbb{R}^n : d(x, A) < t\} = A + t\,B$$
  where $B = \{x \in \mathbb{R}^n : d(0, x) < 1\}$ is an *open unit ball* and $d(x, A) = \inf_{y \in A} d(x, y)$.

- **Definition** (***Surface Area of Sets***)
  let $A \subset \mathbb{R}^n$ be a measurable set and denote by $\mathrm{Vol}(A)$ its *Lebesgue measure. The* ***surface area*** *of* A is defined by
  $$\mathrm{Vol}(\partial A) = \lim_{t \to 0} \frac{\mathrm{Vol}(A_t) - \mathrm{Vol}(A)}{t}.$$
  provided that the limit exists. Here A_t denotes *the t-blowup* of A.

- **Remark** (***Isoperimetry Theorem***)
  The classical isoperimetric theorem in $\mathbb{R}^n$ states that, among all sets with ***a given volume***, ***the Euclidean unit ball minimizes the surface area***. This theoerm can be formally stated as below:

- **Theorem 1.4** *(**Isoperimetry Theorem**) [Boucheron et al., 2013, Vershynin, 2018, Wainwright, 2019]*
  Let $A \subset \mathbb{R}^n$ be such that $Vol(A) = Vol(B)$ where $B := \{x \in \mathbb{R}^n : d(0, x) < 1\}$ is an unit ball. Then for any $t > 0$,
  $$Vol(A_t) \geq Vol(B_t) \tag{4}$$
  Moreover, if $Vol(\partial A)$ exists, then
  $$Vol(\partial A) \geq Vol(\partial B). \tag{5}$$

  Proof: By *the Brunn-Minkowski inequality,*
  $$\begin{aligned} \mathrm{Vol}(A_t)^{1/n} = \mathrm{Vol}(A + tB)^{1/n} &\geq \mathrm{Vol}(A)^{1/n} + t\mathrm{Vol}(B)^{1/n} \\ &= (1 + t)\mathrm{Vol}(B)^{1/n} \\ &= \mathrm{Vol}(B_t)^{1/n}, \end{aligned}$$

establishing the first statement. The second follows simply because

$$\mathrm{Vol}(A_t) - \mathrm{Vol}(A) \geq \mathrm{Vol}(B)((1+t)^n - 1) \geq nt\mathrm{Vol}(B)$$

where $(1+t)^n \geq 1 + nt$ for $t \geq 0$. Thus $\mathrm{Vol}(\partial A) \geq n\mathrm{Vol}(B)$. The isoperimetric theorem now follows from the fact that $\mathrm{Vol}(\partial B) = n\mathrm{Vol}(B)$. ∎

2 Concentration via Isoperimetry

2.1 Levy's Inequalities

- **Remark** We can generalize the classical isoperimety problem to a probability space $(\mathcal{X}, \mathcal{B}[\mathcal{X}], \mathbb{P})$ where $\mathcal{X}$ is a *metric space* with metric d, $\mathcal{B}[\mathcal{X}]$ is the Borel σ-algregbra and $\mathbb{P}$ is a probability measure on $\mathcal{B}[\mathcal{X}]$. Let $B := \{x \in \mathbb{R}^n : d(0, x) < 1\}$. The classical isoperimetry problem aims at finding the set $A^* \subset \mathcal{X}$ that ***minimizes the surface area***

  $$\mathbb{P}(\partial A) = \lim_{t \to 0} \frac{\mathbb{P}(A_t) - \mathbb{P}(A)}{t}$$

  This is equivalent to find subset A in $\mathcal{X}$ with ***minimal t-blowup*** for given p, and for all $t > 0$

  $$A^* := \inf_{A \subset \mathcal{X} : \mathbb{P}(A) \geq p} \mathbb{P}(A_t), \quad \forall t > 0$$

  where

  $$A_t = A + tB = \{x \in \mathcal{X} : \exists y \in A \text{ s.t. } d(x,y) < t\} = \left\{x \in \mathcal{X} : \inf_{y \in A} d(x,y) := d(x, A) < t\right\}.$$

  We write the definition formally.

- **Definition** (***Isoperimetry Problem***) [Boucheron et al., 2013]
  Given a ***metric space*** $\mathcal{X}$ with corresponding *distance* d, consider ***the measure space*** formed by $\mathcal{X}$, *the σ-algebra* of all ***Borel sets** of* $\mathcal{X}$, and a probability measure $\mathbb{P}$. Let X be a *random variable* taking values in $\mathcal{X}$, distributed according to $\mathbb{P}$.

  <u>***The isoperimetric problem***</u> in this case is the following: given $p \in (0, 1)$ and $t > 0$, ***determine the sets*** A with $\mathbb{P}[X \in A] \geq p$ for which *the measure*

  $$\mathbb{P}[d(X, A) \geq t]$$

  is ***maximal***.

- **Remark** (***Isoperimetric Inequalities***)
  Even though the exact solution is only known in a few special cases, useful *bounds* for $\mathbb{P}[d(X, A) \geq t]$ can be derived under remarkably general circumstances. *Such bounds are usually referred to as* <u>***isoperimetric inequalities***</u>.

- **Definition** (***Concentration Function***) [Boucheron et al., 2013, Wainwright, 2019]
  <u>***The concentration function***</u> $\alpha : [0, \infty) \to \mathbb{R}_+$ associated with ***metric measure space*** $((\mathcal{X}, d), \mathbb{P})$ is given by

  $$\alpha_{\mathbb{P},(\mathcal{X},d)}(t) := \sup_{A \subset \mathcal{X} :\, \mathbb{P}(A) \geq \frac{1}{2}} \mathbb{P}[d(X, A) \geq t] = \sup_{A \subset \mathcal{X} :\, \mathbb{P}(A) \geq \frac{1}{2}} \mathbb{P}(A_t^c)$$

where $A_t := A + tB = \{x \in \mathcal{X} : d(x, A) < t\}$ is *the t-blowup* of $A \subset \mathcal{X}$. We simply denote it as $\alpha(t)$.

Thus the optimal A^* for isoperimetry problem is the one that attains the $\alpha(t) = \mathbb{P}(A_t^c)$.

- **Theorem 2.1** *(**Levy's Inequalities**)[Boucheron et al., 2013, Wainwright, 2019]*
  For any Lipschitz function $f : \mathcal{X} \to \mathbb{R}$,

$$\begin{aligned} \mathbb{P}\{f(X) \geq Med(f(X)) + t\} \leq \alpha_{\mathbb{P}}(t) \\ \mathbb{P}\{f(X) \leq Med(f(X)) - t\} \leq \alpha_{\mathbb{P}}(t). \end{aligned} \tag{6}$$

  *where $Med(f(X))$ is **the median** of $f(X)$, i.e.*

$$\mathbb{P}\{f(X) \leq Med(f(X)\} \geq \frac{1}{2}, \quad and \;\; \mathbb{P}\{f(X) \geq Med(f(X)\} \geq \frac{1}{2}.$$

  Proof: Consider the set $A = \{x : f(x) \leq \mathrm{Med}(f(X))\}$. By the definition of a *median*, $\mathbb{P}(A) \geq \frac{1}{2}$. On the other hand, by *the Lipschitz property* of f, for any $x, y \in \mathcal{X}$,

$$|f(x) - f(y)| \leq d(x, y).$$

  So for all $y \in A$, $f(y) \leq \mathrm{Med}(f(X))$

$$\begin{aligned} f(x) - \mathrm{Med}(f(X)) &\leq f(x) - f(y) \leq d(x, y) \\ \Rightarrow f(x) - \mathrm{Med}(f(X)) &\leq \inf_{y \in A} d(x, y) := d(x, A). \end{aligned}$$

  Equivalently,

$$\begin{aligned} A_t := \{x \in \mathcal{X} : d(x, A) < t\} &\subseteq \{x \in \mathcal{X} : f(x) < \mathrm{Med}(f(X)) + t\} \\ \mathbb{P}(A_t^c) &\geq \mathbb{P}\{f(X) \geq \mathrm{Med}(f(X)) + t\} \end{aligned}$$

  The first inequality now follows from the definition of the concentration function. The second inequality follows from the first by considering f. ∎

- **Remark** For L-Lipschitz function f, the inequality becomes

$$\mathbb{P}\{f(X) - \mathrm{Med}(f(X)) \geq t\} \leq \alpha\left(\frac{t}{L}\right), \quad \mathbb{P}\{f(X) - \mathrm{Med}(f(X)) \leq -t\} \leq \alpha\left(\frac{t}{L}\right).$$

- **Theorem 2.2** *(**Converse of Levy's Inequalities**)[Boucheron et al., 2013, Wainwright, 2019]*
  *If $\beta : \mathbb{R}_+ \to [0, 1]$ is a function such that for **every Lipschitz function** $f : \mathcal{X} \to \mathbb{R}$*

$$\mathbb{P}\{f(X) - Med(f(X)) \geq t\} \leq \beta(t). \tag{7}$$

  then $\beta(t) \geq \alpha_{\mathbb{P}}(t)$.

  Proof: Note that for any $A \subset \mathcal{X}$, the function f_A defined by $f_A(x) = d(x, A)$ is *Lipschitz* since

$$|f_A(x) - f_A(y)| = |d(x, A) - d(y, A)| \leq d(x, y).$$

Also, if $P(A) \geq 1/2$, then 0 is a median of $f_A(X)$, since

$$\mathbb{P}\{f_A(x) \leq 0\} = \mathbb{P}\{d(X, A) \leq 0\} = \mathbb{P}(A) \geq \frac{1}{2}.$$

Therefore

$$\alpha(t) := \sup_{A \subset \mathcal{X}: \mathbb{P}(A) \geq 1/2} \mathbb{P}\{f_A(x) - \mathrm{Med}(f_A(X)) \geq t\} \leq \beta(t). \quad \blacksquare$$

- **Proposition 2.3** ***(Levy's Inequalities for Mean)****[Boucheron et al., 2013, Wainwright, 2019]*
  If $\beta : \mathbb{R}_+ \to [0, 1]$ is a function such that for ***every Lipschitz function*** *$f : \mathcal{X} \to \mathbb{R}$*

  $$\mathbb{P}\{f(X) - \mathbb{E}[f(X)] \geq t\} \leq \beta(t). \tag{8}$$

  then $\beta(t) \geq \alpha_{\mathbb{P}}(t/2)$.

- **Remark** (***Isoperimetric Inequalities*** $\Leftrightarrow$ ***Concentration of Lipschitz Functions***)
  The first result points out that *isoperimetric inequalities* (more precisely, ***upper bounds*** *for* ***the concentration function***) imply *concentration of Lipschitz functions.*

  The converse shows that *concentration of Lipschitz functions* implies an *isoperimetric inequality.* In other word, *among all upper bounds* of $\mathbb{P}(A_t^c)$ for fixed A_t,

- **Corollary 2.4** *(****Concentration of Measure on Hamming Metric Space****) [Boucheron et al., 2013]*
  Consider independent random variables $Z_1, \ldots, Z_n$ *taking their values in a* (measurable) set $\mathcal{X}$ *and denote the vector of these variables by $Z = (Z_1, \ldots, Z_n)$ taking its value in $\mathcal{X}^n$. For an arbitrary (measurable) set $A \subset \mathcal{X}^n$, we write $\mathbb{P}(A) = \mathbb{P}(Z \in A)$. The* ***Hamming distance*** *$d_H(x, y)$ between the vectors $x, y \in \mathcal{X}^n$ is defined as* ***the number of coordinates*** *in which x and y* ***differ****. Then for any $t > 0$,*

  $$\mathbb{P}\left\{d_H(x, A) \geq \sqrt{\frac{n}{2}\log\frac{1}{\mathbb{P}(A)}} + t\right\} \leq \exp\left(-\frac{2t^2}{n}\right) \tag{9}$$

  Proof: As we shown in previous proof, $f_A(x) = d_H(x, A)$ is a Lipschitz function with respect to Hamming distance d_H. It follows from the definition that

  $$\sup_{x \in \mathcal{X}^n, y_i \in \mathcal{X}} \left| f_A(x) - f_A(\widetilde{x}^{(i)}) \right| \leq d_H(x, \widetilde{x}^{(i)}) = 1$$

  where $\widetilde{x}^{(i)} = (x_1, \ldots, x_{i-1}, y_i, x_{i+1}, \ldots, x_n)$, so f_A has the bounded difference property. By bounded difference inequality,

  $$\mathbb{P}\{\mathbb{E}[f_A(Z)] - f_A(Z) \geq t\} \leq \exp\left(-\frac{2t^2}{n}\right).$$

  Taking $t = \mathbb{E}[f_A(Z)] = \mathbb{E}[d_H(Z, A)]$, the left-hand side becomes $\mathbb{P}\{f_A(Z) \leq 0\} = \mathbb{P}\{d_H(Z, A) \leq 0\} = \mathbb{P}(A)$. Then the inequality becomes

  $$\mathbb{P}(A) \leq \exp\left(-\frac{2}{n}\left(\mathbb{E}[d_H(Z, A)]\right)^2\right)$$
  $$\Rightarrow \mathbb{E}[d_H(Z, A)] \leq \sqrt{\frac{n}{2}\log\frac{1}{\mathbb{P}(A)}}.$$

Then, by using the bounded difference inequality again, we obtain

$$\mathbb{P}\left\{d_H(Z,A) \geq \sqrt{\frac{n}{2}\log\frac{1}{\mathbb{P}(A)}} + t\right\} \leq \mathbb{P}\left\{d_H(Z,A) \geq \mathbb{E}\left[d_H(Z,A)\right] + t\right\} \leq \exp\left(-\frac{2t^2}{n}\right). \quad \blacksquare$$

- **Remark** (***Concentration of Measure***)
  To interpret the result in (9), we see that on the left-hand side we have the measure of the set of points whose Hamming distance is at least $t+\sqrt{\frac{n}{2}\log\frac{1}{\mathbb{P}(A)}}$ away from A. This inequality means that for A with ***small measure*** $\mathbb{P}(A)$, the measure of points whose ***Hamming distance*** from A is *more than* $O\left(\sqrt{n}\right)$ is ***extremely small***.

  In other words, ***product measure*** *on Hamming metric space are* ***concentrated*** *on* ***extremely small sets***. This phenomenon is called "***concentration of measure***".

- **Example** (***Bounded Difference Property*** $\Leftrightarrow$ ***Lipschitz Condition w.r.t. Hamming Distance***)
  Note that any function with ***bounded difference property*** is ***Lipschitz function*** with respect to ***Hamming distance***.

$$\begin{aligned}
&\sup_{x\in\mathcal{X}^n, y_i\in\mathcal{X}} \left|f(x_1,\ldots,x_n) - f(x_1,\ldots,x_{i-1},y_i,x_{i+1},\ldots,x_n)\right| \\
&\leq c_i = c_i\, d_H((x_1,\ldots,x_n),(x_1,\ldots,x_{i-1},y_i,x_{i+1},\ldots,x_n)), \quad 1\leq i\leq n \\
\Rightarrow |f(x)-f(y)| &= \left|\sum_{i=1}^{n}(f(x_{(i-1)}) - f(x_{(i)}))\right| \\
&\leq \sum_{i=1}^{n}\left|f(x_{(i-1)}) - f(x_{(i)})\right| \\
&\leq \sum_{i=1}^{n} c_i \mathbb{1}\left\{x_{(i-1)}[i] \neq x_{(i)}[i]\right\} \\
&= d_{H,c}(x,y)
\end{aligned}$$

  where $x_{(i)}$ is replicate of $x_{(i-1)}$ except for i-th component, which is replaced by y_i. Note that $x_{(0)} = x$ and $x_{(n)} = y$. Therefore, *the bounded difference inequality* can be seen as *an isoperimetry inequality* for *Lipschitz function with respect to Hamming distance.*

$$\mathbb{P}\left\{f(Z) - \mathbb{E}\left[f(Z)\right] \geq t\right\} \leq \exp\left(-\frac{2t^2}{n}\right)$$

2.2 Isoperimetric Inequalities on the Unit Sphere

- **Definition** (***Spherical Cap and its t-Blowup***)
  Let $\mathbb{S}^{n-1} := \{x \in \mathbb{R}^n : \|x\| = 1\}$ be the $(n-1)$-*dimensional* ***unit sphere***. The ***intersection*** of a ***half-space*** and $\mathbb{S}^{n-1}$ is called a ***spherical cap***. In particular, for some $y \in \mathbb{R}^n$, denote the associated spherical cap as

$$H_y := \left\{x \in \mathbb{S}^{n-1} : \langle x\,,\, y\rangle \leq 0\right\}$$

  With some simple geometry, it can be shown that its t-*blowup* corresponds to the set

$$H_y^t := \left\{x \in \mathbb{S}^{n-1} : \langle x\,,\, y\rangle < \sin(t)\right\}$$

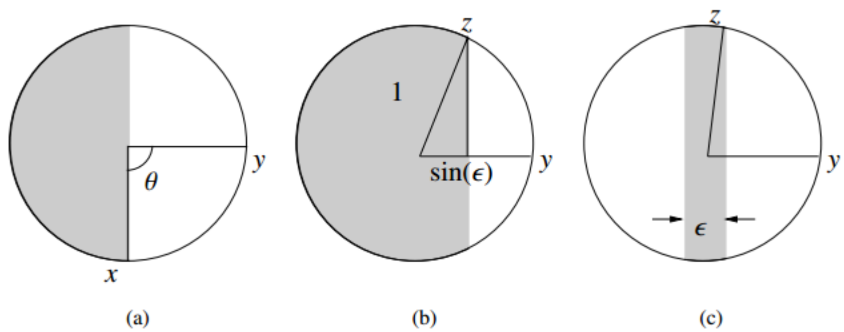

Figure 3.1 (a) Idealized illustration of the sphere $\mathbb{S}^{n-1}$. Any vector $y \in \mathbb{S}^{n-1}$ defines a hemisphere $H_y = \{x \in \mathbb{S}^{n-1} \mid \langle x, y\rangle \le 0\}$, corresponding to those vectors whose angle $\theta = \arccos\langle x, y\rangle$ with y is at least $\pi/2$ radians. (b) The ϵ-enlargement of the hemisphere H_y. (c) A central slice $T_y(\epsilon)$ of the sphere of width ϵ.

Figure 2: spherical cap and t-blowup. [Wainwright, 2019]

- **Theorem 2.5** ***(Isoperimetry Theorem on Unit Sphere)*** *[Boucheron et al., 2013, Vershynin, 2018, Wainwright, 2019]*
  Let A be a subset of the sphere $\mathbb{S}^{n-1}$, and let σ denote the ***normalized area*** *on that sphere. Let $t > 0$. Then, among all sets $A \subset \mathbb{S}^{n-1}$ with given area $\sigma(A)$, the* ***spherical caps minimize the area of the neighborhood*** *$\sigma(A_t)$, where*

$$A_t := \left\{x \in \mathbb{S}^{n-1} : \exists y \in A \text{ such that } \|x - y\| < t\right\}$$

- **Remark** Define a *metric* ρ on sphere $\mathbb{S}^{n-1}$ as

$$\rho(x, y) := \arccos(\langle x\,,\, y\rangle)$$

  Thus $(\mathbb{S}^{n-1}, \rho)$ is a ***metric space***. Let $\mathbb{P}$ be uniform distribution on $\mathbb{S}^{n-1}$ so that $((\mathbb{S}^{n-1}, \rho), \mathbb{P})$ is a probability space.

- **Proposition 2.6** ***(Isoperimetric Inequalities for Uniform Distribution over Sphere)*** *[Boucheron et al., 2013, Vershynin, 2018, Wainwright, 2019]*
  Let $\mathbb{S}^{n-1} := \{x \in \mathbb{R}^n : \|x\| = 1\}$ be the $(n-1)$-dimensional ***unit sphere****. For any $t \in [0, 1]$,*

$$\alpha_{\mathbb{S}^{n-1}}(t) \le c \exp\left(-\frac{nt^2}{2}\right) \tag{10}$$

  for some constant c.

  Proof: Consider spherical cap

$$C(y, 0) := \left\{x \in \mathbb{S}^{n-1} : \langle x\,,\, y\rangle \ge 0\right\}$$

  and its *t-blowup*

$$C(y, t) := \left\{x \in \mathbb{S}^{n-1} : \langle x\,,\, y\rangle \ge t\right\}.$$

  According to *the isoperimetry theorem on unit sphere*, the concentration function for uniform distribution over $\mathbb{S}^{n-1}$

$$\alpha_{\mathbb{S}^{n-1}}(t) = \mathbb{P}(C(y, t)).$$

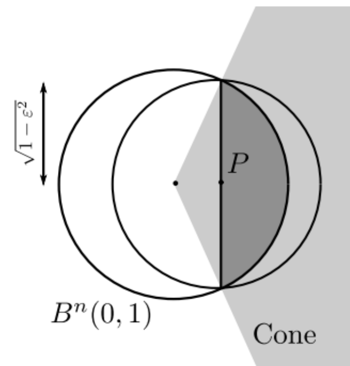

Figure 2: Small ε.

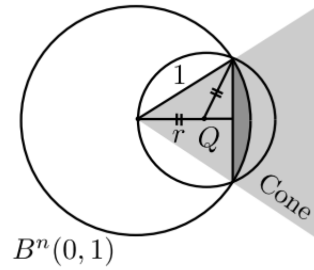

Figure 3: Large ε. By the congruence $\frac{1/2}{r} = \frac{\varepsilon}{1}$.

Figure 3: proof for upper bound of area of spherical cap (left) for small t (right) for large t

Note that $\mathbb{P}\left(C(y,0)\right) \leq 1/2$. In order to bound the concentration function from above, consider for small $t \in [0, 1/\sqrt{2}]$,

$$\begin{aligned}
\alpha_{\mathbb{S}^{n-1}}(t) = \mathbb{P}\left(C(y,t)\right) &= \frac{\mathrm{Vol}(B^n(0,1) \cap \mathrm{Cone})}{\mathrm{Vol}(B^n(0,1))} \\
&\leq \frac{\mathrm{Vol}(B^n(P, \sqrt{1-t^2}))}{\mathrm{Vol}(B^n(0,1))} \\
&= (\sqrt{1-t^2})^n \\
&\leq \exp\left(-\frac{nt^2}{2}\right)
\end{aligned}$$

For $t \in [1/\sqrt{2}, 1)$, it is enough to consider a different auxiliary ball which includes the set $\mathrm{Cone} \cap B^n(0,1)$. We obtain

$$\begin{aligned}
\alpha_{\mathbb{S}^{n-1}}(t) = \mathbb{P}\left(C(y,t)\right) &\leq \frac{\mathrm{Vol}(B^n(Q,r))}{\mathrm{Vol}(B^n(0,1))} \\
&= r^n = \left(\frac{1}{2t}\right)^n \\
&\leq \exp\left(-\frac{nt^2}{2}\right)
\end{aligned}$$

where the last inequality is from $e^{x^2/2} \leq 2x$ for $x \in [1/\sqrt{2}, 1]$. Due to convexity, this is only to be checked at the boundary of our interval $[1/\sqrt{2}, 1]$, ∎

- By Levy's inequality, we have the following proposition

  Proposition 2.7 ***(Lipschitz Function on*** $\mathbb{S}^{n-1}$*) [Wainwright, 2019]*
  For any 1-Lipschitz function f defined on the sphere $\mathbb{S}^{n-1}$, we have the two-sided bound

$$\mathbb{P}\left\{|f(Z) - Med(f(Z))| \geq t\right\} \leq \sqrt{2\pi} \exp\left(-\frac{nt^2}{2}\right) \tag{11}$$

Moreover, replacing median by the mean, we have

$$\mathbb{P}\left\{|f(Z) - \mathbb{E}\left[f(Z)\right]| \geq t\right\} \leq 2\sqrt{2\pi}\exp\left(-\frac{nt^2}{8}\right) \tag{12}$$

- **Exercise 2.8** ***(The Blow-Up Phenomenon)***
  Let A be a subset of the sphere $\sqrt{n}\mathbb{S}^{n-1}$ such that

  $$\mathbb{P}\left(A\right) > 2\exp\left(-cs^2\right) \textit{ for some } s > 0;$$

  1. *Prove that $\mathbb{P}(A_s) > 1/2$.*
  2. *Deduce from this that for any $t \geq s$,*

     $$\mathbb{P}\left(A_{2t}\right) > 1 - 2\exp\left(-ct^2\right).$$

     Here $c > 0$ is the absolute constant in upper bound of concentration function.

- **Remark** (***Zero-One Law for Independent Variables***) [Vershynin, 2018]
  The blow-up phenomenon we just saw may be quite *counter-intuitive* at first sight. How can an exponentially small set A undergo such a dramatic transition to an exponentially large set A_{2t} under such a small perturbation $2t$? (Remember that t can be much smaller than the radius $\sqrt{n}$ of the sphere.)

  However perplexing this may seem, this is *a typical phenomenon in* ***high dimensions***. It is *reminiscent* of ***zero-one laws*** in *probability theory*, which basically state that *events that are determined by many random variables* tend to have *probabilities either zero or one*.

2.3 Gaussian Isoperimetric Inequalities and Concentration of Gaussian Measure

2.4 Edge Isoperimetric Inequality on the Binary Hypercube

2.5 Vertex Isoperimetric Inequality on the Binary Hypercube

2.6 Convex Distance Inequality

References

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