The KLS Conjecture

Amit Rajaraman

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§0. Notation

- We refer to measures by greek symbols such as μ and ν and their densities by lowercase alphabets beginning from p.
- B refers to the Euclidean ball of radius 1 in $\mathbb{R}^n$ (the value of n is usually understandable from context).
- Given a measure μ on $\mathbb{R}^n$ and an $(n-1)$-dimensional surface(?) S in $\mathbb{R}^n$, $\mu^+(S)$ refers to the "surface area" of the set S, that is,
$$\mu^+(X) = \lim_{\varepsilon \to 0} \frac{\mu(X + \varepsilon B)}{2\varepsilon}.$$
Alternatively, if $X \subseteq \mathbb{R}^n$ is compact, then
$$\mu^+(\partial X) = \lim_{\varepsilon \to 0} \frac{\mu(X + \varepsilon B) - \mu(X)}{\varepsilon}.$$
- While needles in [KLS95] refer to one-dimensional segments with a polynomial factor (ℓ^{n-1} where ℓ is linear) in particular, we use them more generally to refer to log-concave measures with a one-dimensional support.

§1. Measure Disintegration

1.1. Introduction

To begin with, let us describe a needle decomposition procedure given in [LV18] to prove the KLS Conjecture. Suppose that we are given a log-concave measure μ with density p with compact convex support K. Let us also fix a subset $E \subseteq K$ of measure $1/2$. We would like to bound $\mu^+(\partial E)$ below (over all such E).
Now, suppose that we have some hyperplane H that divides space into two half-spaces H_1 and H_2. Let $K_i = K \cap H_i$ and further assume that $\mu(E \cap H_i) = \frac{1}{2}\mu(K_i)$ for each i. Consider the measures μ_1 and μ_2 with densities given by

$$p_i(x) = \begin{cases} p(x)\frac{\mu(K)}{\mu(K_i)}, & x \in K_i, \\ 0, & \text{otherwise.} \end{cases}$$

Observe that

$$\begin{aligned} p &= p_1 \frac{\mu(K_1)}{\mu(K)} + p_2 \frac{\mu(K_2)}{\mu(K)} \\ \mu &= \mu_1 \frac{\mu(K_1)}{\mu(K)} + \mu_2 \frac{\mu(K_2)}{\mu(K)} \end{aligned} \tag{1.1}$$

More generally, suppose we have some space Ω with a probability measure ν on it such that

$$\mu = \int_\Omega \mu_\omega \, \mathrm{d}\nu(\omega), \tag{1.2}$$

where the (μ_ω) are log-concave measures on $\mathbb{R}^n$. In the above example, we can take $\Omega = \{1, 2\}$ and $\nu(\{i\}) = \mu(K_i)/\mu(K)$ for $i \in \Omega$.
Then, given any set E of measure $1/2$, we have

$$\begin{aligned}\mu^+(\partial E) &= \int_\Omega \mu_\omega^+(\partial E)\,\mathrm{d}\nu(\omega) \\ &\geq \int_\Omega \psi_\omega \mu_\omega(E)(1-\mu_\omega(E))\,\mathrm{d}\nu(\omega),\end{aligned} \tag{1.3}$$

where ψ_ω is the isoperimetric constant of μ_ω. If we manage to bound the expression on the right below by some constant independent of E, then the KLS conjecture follows. It is also worth noting that the decomposition we choose may be dependent on E itself, we only require that the lower bound constant does not depend on this choice of E.

1.2. A proof of the $n^{-1/2}$ bound using needle decompositions

"Needle decomposition" refers to the process of performing the step we used to obtain (1.1) until the bodies K_ω become one-dimensional. We repeatedly split the bodies in a way that the quantity $\mu_\omega(E)$ remains constant at $1/2$. Suppose that we do so and the final limiting set of needles is $(K_\omega)_{\omega\in\Omega}$. Then, we can use one-dimensional isoperimetry to get that for any ω, $\psi_\omega \gtrsim \|A_\omega\|_{\mathrm{op}}^{-1/2}$. We also have that $\mu_\omega(E) = 1/2$, so

$$\mu^+(\partial E) \gtrsim \int_\Omega \|A_\omega\|_{\mathrm{op}}^{-1/2}\,\mathrm{d}\nu(\omega). \tag{1.4}$$

We wish to bound the integral on the right below.

To do so, consider (1.2) (or rather, the similar expression for the density p). Then, we have that

$$\int_{\mathbb{R}^n} p(x)xx^\top\,\mathrm{d}x = \int_\Omega \int_{\mathbb{R}^n} p_\omega(x)xx^\top\,\mathrm{d}x\,\mathrm{d}\nu(\omega).$$

Thus,

$$A + bb^\top = \int_\Omega A_\omega + b_\omega b_\omega^\top\,\mathrm{d}\nu(\omega), \tag{1.5}$$

where A and b (resp. A_ω and b_ω) refer to the covariance matrix and barycenter of μ (resp. μ_ω) respectively.
Assume without loss of generality that $b = 0$. Taking the trace on either side of the above expression,

$$\begin{aligned}\mathrm{Tr}(A) &= \int_\Omega \mathrm{Tr}(A_\omega) + \|b_\omega\|^2\,\mathrm{d}\nu(\omega) \\ &\geq \int_\Omega \|A_\omega\|_{\mathrm{op}}\,\mathrm{d}\nu(\omega),\end{aligned}$$

where the inequality follows from the fact that A_ω is a covariance matrix so is positive semi-definite. One can then use Hölder's inequality to get

$$\left(\int_\Omega \|A_\omega\|_{\mathrm{op}}\,\mathrm{d}\nu(\omega)\right)\left(\int_\Omega \|A_\omega\|_{\mathrm{op}}^{-1/2}\,\mathrm{d}\nu(\omega)\right)^2 \geq 1$$

and so,

$$\int_\Omega \|A_\omega\|_{\mathrm{op}}^{-1/2}\,\mathrm{d}\nu(\omega) \gtrsim \mathrm{Tr}(A)^{-1/2}.$$

Substituting this back in (1.4), we get $\psi_p \gtrsim \mathrm{Tr}(A)^{-1/2}$, that is, $\psi_n \gtrsim n^{-1/2}$.

1.3. An alternate way to look at stochastic localization

Let us return to (1.3). In the above method of needle decomposition, we attempted to exercise control over the quantity $\mu_\omega(E)(1-\mu_\omega(E))$ for all ω by fixing $\mu_\omega(E)$ at $1/2$.

How does stochastic localization fit into this? Instead of controlling $\mu_\omega(E)$, we try to control ψ_ω by defining a martingale (p_t) whose isoperimetric constant is easily bounded. That is, $\mathbf{E}[p_t] = p$ (this is just an integral of the form of (1.1)) and further, the isoperimetric constant of μ_t is lower bounded by $t^{1/2}$. Then, the problem comes down to estimating

$$\int_\Omega \mu_t(E)(1-\mu_t(E))\,\mathrm{d}\nu(\omega),$$

which is exactly what papers such as [Che21] do.

1.4. What next?

Going back to needle decompositions again, we wish to show that there exists a needle decomposition conserving $\mu_\omega(E) = 1/2$ such that

$$\int_\Omega \frac{1}{\|A_\omega\|_{\mathrm{op}}^{1/2}}\,\mathrm{d}\nu(\omega) \gtrsim \|A\|_{\mathrm{op}}^{-1/2}.$$

(1.5) for $b = 0$ gives

$$\|A\|_{\mathrm{op}} = \left\| \int_\Omega A_\omega + b_\omega b_\omega^\top \,\mathrm{d}\nu(\omega) \right\|_{\mathrm{op}}.$$

Therefore, it would suffice to show that

$$\int_\Omega \frac{1}{\|A_\omega\|_{\mathrm{op}}^{1/2}}\,\mathrm{d}\nu(\omega) \gtrsim \left\| \int_\Omega A_\omega + b_\omega b_\omega^\top \,\mathrm{d}\nu(\omega) \right\|_{\mathrm{op}}^{-1/2}$$

for some needle decomposition that conserves $\mu_\omega(E)$.[1]

Using Hölder's inequality as we did in the proof of the $n^{-1/2}$ bound, it is seen that it suffices to show

$$\int_\Omega \|A_\omega\|_{\mathrm{op}}\,\mathrm{d}\nu(\omega) \lesssim \left\| \int_\Omega A_\omega + b_\omega b_\omega^\top \,\mathrm{d}\nu(\omega) \right\|_{\mathrm{op}}$$

for some needle decomposition preserving $\mu_\omega(E)$ (it would in fact be enough to show this with some set $A \subseteq \Omega$ instead of Ω such that $\nu(A)$ is lower-bounded by a constant).
Neglecting the $b_\omega b_\omega^\top$ term, it suffices to show that

$$\int_\Omega \|A_\omega\|_{\mathrm{op}}\,\mathrm{d}\nu(\omega) \lesssim \left\| \int_\Omega A_\omega \,\mathrm{d}\nu(\omega) \right\|_{\mathrm{op}}. \tag{1.6}$$

The above inequality essentially asks if there exists a needle decomposition where the needles are "nearly aligned". Indeed, if the segments of the needles are perfectly aligned, then equality holds above. We are allowing a constant factor of leeway. If the direction of the one-dimensional body K_ω is u_ω, then the above is equivalent to

$$\sup_{\|\zeta\|\le 1} \int_\Omega \mathbf{Var}_{x\sim p_\omega}(x)\langle \zeta, u_\omega\rangle^2\,\mathrm{d}\nu(\omega) \gtrsim \int_\Omega \mathbf{Var}_{x\sim p_\omega}(x)\,\mathrm{d}\nu(\omega) \tag{1.7}$$

[1] Is this inequality equivalent to the KLS Conjecture? Do there exist needle decompositions not obtained by the bisection method that conserve $\mu_\omega(E)$ and satisfy the above inequality?

§2. More on decompositions

2.1. Hyperplane bisections

As before, suppose we have a log-concave probability measure μ with density p on the body K, and we fix some $E \subseteq K$ with $\mu(E) = 1/2$. Let us define the function $f_{E,K} : \mathbb{R}^n \setminus \{0\} \to \mathbb{R}$ by

$$f_{E,K}(x) = \left| \int_{\{z \in \mathbb{R}^n : \langle z, x \rangle \geq \|x\|^2\}} p(y)(\mathbb{1}_E - \mathbb{1}_{\mathbb{R}^n \setminus E}) \, \mathrm{d}y \right|.$$

That is, if H_x is the hyperplane defined by x (orthogonal to x and passing through it) and H_x^+ is either of the resulting halfspaces, the value of the above function at x is equal to $|\mu(E \cap H_x^+) - \mu((\mathbb{R}^n \setminus E) \cap H_x^+)|$.
This serves as a measure of how "imbalanced" the hyperplane corresponding to x is – $f_{E,K}(x) = 0$ iff the hyperplane corresponds to x is a bisecting hyperplane (where bisecting means that $\mu(E \cap K_\omega) = \frac{1}{2}\mu(K_\omega)$, as in needle decompositions).
For nice(?) E, $f_{E,K}$ is continuous.

The primary tool used in [LS93] to prove the localization lemma was that there exists a bisecting hyperplane passing through any $(n-2)$-dimensional affine space. How would this translate in terms of the above defined function?
Suppose we have an $(n-2)$-dimensional affine space orthogonal to the subspace spanned by $y, z \in \mathbb{R}^n$ and passing through y.
Suppose that x defines a hyperplane containing this affine space. Then x is orthogonal to the plane, and so orthogonal to the space itself. That is, it must lie in the subspace spanned by y, z. Further, $y - x$ is orthogonal to x. That is, the set of all these x forms a circle passing through 0 contained in the 2-dimensional subspace spanned by y, z.
The conclusion of the localization method is that for any circle S passing through 0, either

- $f(w) = 0$ for some $w \in S \setminus \{0\}$ or
- The limit of $f(w)$ as w goes to 0 along the circle is equal to 0 – this corresponds to a bisecting hyperplane passing through the origin itself. It is not too difficult to check that this is well-defined and that the directional limit along either direction of the circle is the same.

More generally, suppose we have some smooth curve C in $\mathbb{R}^n$ that passes through the origin. Then, as before, either $f(w) = 0$ for some $w \in C \setminus \{0\}$ or one of the directional limits at 0 (along C) is equal to 0.

A consequence of this nice property is that given any non-zero $x \in \mathbb{R}^n$, there exists a "barrier" curve C in $\mathbb{R}^n$ separating x from 0 such that $f(y) = 0$ for any $y \in C$.
An interesting question is to generally characterize these functions.

2.2. Aligned 2-dimensional decompositions are always possible

Suppose we have an n-dimensional body K with $n > 2$ along with some direction u in $\mathbb{R}^n$. We claim that it is possible to decompose this into a set of $(n-1)$-dimensional bodies $\{K_\omega\}$ such that any of these bodies contains our specified direction u (meaning that a translational shift of $\operatorname{span}(\{u\})$ is contained in the minimal affine space containing any K_ω).

To prove this, assume without loss of generality that $u = e_n$. Consider the set of $(n-2)$-dimensional affine spaces

$$S = \{\{x \in \mathbb{R}^n : x_i = q_1, x_j = q_2\} : q_1, q_2 \in \mathbb{Q}, 1 \leq i < j \leq n-1\}.$$

This is similar to the argument involved in [LS93] except that we only consider the set of $(n-2)$-dimensional affine spaces that contain u. As the argument goes there, all the bodies must decompose into at most $(n-1)$-dimensional bodies in the limiting step – if not, then there exists some affine space in S that intersects the n-dimensional body, and choosing the corresponding bisecting hyperplane results in a contradiction.

In fact, it turns out that we can decompose it into a set of 2-dimensional bodies that all contain our specified direction!

This is easily done using induction on n. Reducing the n-dimensional body to a set of $(n-1)$-dimensional bodies and then each of these smaller bodies to 2-dimensional bodies gets the job done. It should be noted that this argument does not work out if the body under consideration is 2-dimensional, since it does not make sense to have a 0-dimensional affine space containing our direction.

A natural next question is: can we give up perfect alignedness in exchange for near alignedness, which is all we really need to show KLS?

2.3. A potential function

Let us fix μ, p, K, and E as usual. Also suppose we have some direction u. We wish to decompose the body into needles in a way that all of them are nearly in the direction of u. Equivalently, the hyperplanes chosen for bisection should all nearly contain u. That is, the set of x corresponding to the hyperplanes $\{H_x\}$ must all be nearly orthogonal to u. So, at each step, the x chosen must be such that $\langle x, u\rangle$ is small – more precisely, $1 - \frac{\langle x,u\rangle^2}{\|x\|^2} \gtrsim 1$.
Also, as seen from Equation (1.3), all we really want is that $\mu_\omega(E)(1-\mu_\omega(E)) \gtrsim 1$, it might be fine to instead just minimize $f_{E,K}$ instead of ensuring that it is exactly equal to 0. So, one may choose the x corresponding to the bisecting hyperplane at each step by constructing a potential function such as

$$\Phi(x) = \left(1 + f_{E,K}(x)\right)\left(1 + \frac{|\langle x, u\rangle|}{\|x\|}\right)$$

and at each step, choosing the x that minimizes Φ. The reason for adding the 1 is that otherwise, it would be minimized if the corresponding term is 0. Note that the argument of [LS93] is just the above potential without the second term (not taking alignment into account at all).

References

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