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SAMPLING FROM LOG-CONCAVE  
DISTRIBUTIONS

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# SAMPLING FROM LOG-CONCAVE DISTRIBUTIONS

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## 1 Introduction

This paper is concerned with the efficient sampling of random points from  $\mathbf{R}^n$  where the underlying density  $F$  is log-concave. This is a natural restriction which is satisfied by many common distributions e.g. the multi-variate normal. The algorithm we use generates a sample path from a Markov chain whose stationary distribution is (close to)  $F$ . The algorithm is based on the Metropolis class of algorithms and has applications in the problem of computing the volume of convex bodies and in statistics. Recent statistical literature has focused on the many applications of Markov chain Monte Carlo algorithms (see Tierney [8]) whereas theoretical bounds on the convergence rate of such algorithms has been limited. This paper provides an explicit bound

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for the convergence rate of the Metropolis algorithm that is polynomial in  $n$  and other parameters of the problem.

Instead of sampling from the continuum of points in  $\mathbf{R}^n$ , we discretize the problem by assuming that  $\mathbf{R}^n$  is divided into a set of hypercubes  $\mathcal{C}_{\mathbf{R}}$  of side  $\delta$  ( $\delta$  is a given small positive real number) and the problem is to choose one of these cubes each with probability proportional to the integral of  $F$  over the cube. [If necessary, a sample from the continuum can then be picked by standard rejection sampling techniques from the cube chosen; we omit details of this.] Secondly, we assume that we have a compact convex set  $K$  and we wish to choose points only from  $K$  (not all of  $\mathbf{R}^n$ ). This is justified because clearly for any positive real number  $\epsilon$ , we can find a compact convex set (for example a ball) such that the integral of  $F$  over the set is at least  $(1 - \epsilon)$  times the integral over  $\mathbf{R}^n$ . While it would suffice to consider the case when  $K$  is a ball, the generality of convex sets is useful in many contexts.

In what follows  $\mathcal{C}$  denotes a subset of the cubes  $\mathcal{C}_{\mathbf{R}}$  whose union contains  $K$ . For example  $\mathcal{C}$  could be the set of cubes  $\mathcal{C}_I(K)$  which have nonempty intersection with  $K$ . Let  $C$  denote the set of centres of these cubes. For  $x \in \mathbf{R}^n$  we denote the cube of side  $\delta$  and centre  $x$  by  $C(x)$ . (Thus  $C(x) \in \mathcal{C}$  if and only if  $x \in C$ .) We choose our sample point  $X$  by performing a random walk over  $C$ . The walk is biased so that its steady state is (close to) what we want and we run the walk until it is close enough to the steady state. The main results of this paper concern the rate of convergence of the walk to its steady state.

We may not be able to compute  $F$  exactly and so we assume we have good approximations  $\bar{F}(x), x \in C$ . Further we assume that  $\bar{F}(x)$  is strictly positive

for all  $x \in C$ .

We can only take advantage of the log-concavity of  $F$  if our grid is sufficiently fine and our approximations  $\bar{F}(x)$  are sufficiently good. In this context we will assume that for some small  $\alpha > 0$

$$(1 + \alpha)^{-1} \bar{F}(x) \leq \bar{F}(y) \leq (1 + \alpha) \bar{F}(x) \quad (1)$$

and

$$(1 + \alpha)^{-1} \delta^{n-1} \bar{F}(x) \leq \int_{C(x) \cap C(y)} F(\xi) d\xi \leq (1 + \alpha) \delta^{n-1} \bar{F}(x) \quad (2)$$

whenever  $C(x), C(y)$  are cubes of  $\mathcal{C}$  sharing a face  $C(x) \cap C(y)$  of dimension  $n - 1$ . Furthermore, we assume

$$(1 + \alpha)^{-1} \delta^n \bar{F}(x) \leq \int_{C(x)} F(\xi) d\xi \leq (1 + \alpha) \delta^n \bar{F}(x) \quad \forall x \in C. \quad (3)$$

When we have  $\bar{F} = F$ , it is easy to check that all three conditions are satisfied if we choose  $\alpha$  to be  $e^{M\delta} - 1$  where  $M$  is the Lipschitz constant of  $\ln F$  with respect to the infinity norm. (i.e.,  $M$  satisfies  $|\ln F(x) - \ln F(y)| \leq M|x - y|_\infty$ ,  $\forall x, y \in K$ ). However, an  $\alpha$  smaller than  $e^{M\delta} - 1$  may satisfy (1)-(3); this is in fact the case for important functions like  $F(x) = e^{-c|x|}$  and  $F(x) = e^{-c|x|^2}$  as tedious, but simple calculations show. This is the reason for our stating the cumbersome conditions (1)-(3). As we will see (Theorems 1 and 2), the rate of convergence to the steady state depends upon  $(1 + \alpha)$ . In typical applications, one would make  $1 + \alpha$  a constant. (For example this can be ensured by choosing  $\delta = O(1/M)$ .)

The walk we consider fits into the scheme of Metropolis algorithms introduced in Metropolis, Rosenberg, Rosenbluth, Teller and Teller [6]. It was used by Applegate and Kannan [1] in their paper on volume computation.

In the following, for any natural number  $m$ , we let  $[m] = \{1, 2, \dots, m\}$  and  $e_1, e_2, \dots, e_m$  are the standard basis vectors of  $\mathbf{R}^m$ .

### The Random Walk

This generates a random sequence  $X_0, X_1, X_2, \dots, X_t, \dots \in C$  where  $X_0$  is picked according to some initial distribution  $p_0(x)$  and  $X_{t+1}$  is obtained from  $X_t$  as follows:

**Step 1** Choose  $j$  randomly from  $[n]$ .      Choose  $\sigma$  randomly from  $\{\pm 1\}$ .

**Step 2** Let  $y = X_t + \sigma e_j$ .

**Step 3** If  $y \notin C$  then  $X_{t+1} = X_t$ , otherwise, put  $X_{t+1} = y$  with probability  $\theta = \text{Min} \{1, \bar{F}(y)/\bar{F}(X_t)\}$  and  $X_{t+1} = X_t$  with probability  $1 - \theta$ .

Formally, the transition probabilities  $P(x, y) = \Pr(X_{t+1} = y \mid X_t = x)$  are given by

$$P(x, y) = \frac{1}{2n} \text{Min} \{1, \bar{F}(y)/\bar{F}(x)\} \text{ for } x \neq y; x, y \text{ adjacent}$$

and

$$P(x, x) = 1 - \sum_{y \neq x} P(x, y).$$

We refer to this as “the random walk” in the paper. It will be useful also to consider a modified random walk. “The modified random walk” has

$$P(x, y) = \frac{\nu}{2n} \text{Min} \{1, \bar{F}(y)/\bar{F}(x)\} \text{ for } x \neq y; x, y \text{ adjacent}$$

and

$$P(x, x) = 1 - \sum_{y \neq x} P(x, y)$$



where  $\nu = 1 - \frac{2\delta^2}{(1+\alpha)^3 nd(d+2\sqrt{n\delta})}$ . In most applications,  $\nu$  will be very close to 1. So the modification can be thought of as : with a small probability, the walk stays put, otherwise does what “the (unmodified) random walk” did.

When  $\mathcal{C} = \mathcal{C}_I(K)$  we will refer to the walk as the “body intersecting” walk. In this case testing whether  $y \in \mathcal{C}$  can be a significant computational problem, but nevertheless polynomially solvable, in general. In specific cases e.g. when  $K = B(0, R)$ , the ball of radius  $R$  centred at the origin the problem is rather trivial.

We will also consider the computationally simpler random walk over those cubes  $\mathcal{C}_C(K)$  in  $\mathcal{C}_R$  whose centres are in  $K$ . We call this the “centre point” random walk.

It is easy to see that the chain is ergodic and thus, there are steady state probabilities  $\pi(x)$  with  $\lim_{t \rightarrow \infty} \Pr(X_t = x) = \pi(x)$  for all  $x$  independent of the distribution of  $X_0$ . It is easy to verify that

$$\pi(x) = \bar{F}(x)/\Delta,$$

where  $\Delta = \sum_{x \in \mathcal{C}} \bar{F}(x)$ . We assume that the  $\bar{F}(x)$  are sufficiently good approximations so that sampling according to  $\pi$  can be considered to be our objective.

Note that this chain is *time reversible* i.e.

$$\pi(x)P(x, y) = \pi(y)P(y, x) \quad \text{for all } x, y \in \mathcal{C}.$$

The main theorem describing the rate of convergence is stated below as Theorem 1 .We use the so-called “chi-squared” distance of the distribution after  $t$  steps to the steady state as a measure of closeness (see Mihail [7] and

Fill [3]). Let  $p_t(x) = \Pr(X_t = x)$  be the distribution after  $t$  steps. Then this distance is given by

$$\sum_{x \in \mathcal{C}} \left( \frac{p_t(x)}{\pi(x)} - 1 \right)^2 \pi(x).$$

There are other measures one could use, including the more traditional “variational distance” given by

$$\sum_{x \in \mathcal{C}} |p_t(x) - \pi(x)|.$$

The chi-squared measure turns out to yield stronger theorems and in fact (as Fill points out), one can derive a bound on the variational distance using the bound on the chi-squared distance. (See Corollary 1).

In the following Theorems, 1 and 2, we have a random walk over a set of cubes  $\mathcal{C}$ .

$$T = \bigcup_{D \in \mathcal{C}} D$$

and

$$d = \text{diam}(T),$$

(maximum distance between two points).

Then let

$$\kappa_0 = \frac{d}{4\delta}(d + 2\sqrt{n}\delta)$$

$$\kappa_1 = \frac{18\delta\sqrt{n}}{d}$$

$$\kappa_2 = 9\sqrt{n}(d/2 + \delta(\sqrt{n} + 1))$$

**Theorem 1** *Let  $K$  be a convex set in  $\mathbf{R}^n$ . Let  $\mathcal{C}$  be a subset of  $\mathcal{C}_{\mathbf{R}}$  (with  $\delta \leq d/10$ ) such that  $K \subseteq T$ . Let  $C$  be the set of centres of these cubes. Let  $S$  be*

the set of centres of those cubes in  $\mathcal{C}$  which are not wholly contained in  $K$  and let  $\bar{S} = \mathcal{C} \setminus S$ . Let  $F$  be a log-concave positive real valued function on  $K$  with  $\alpha$  satisfying (1), (2) and (3). Consider the random walk  $X_0, X_1, \dots, X_t, \dots$  described above. Then with  $p_t(x) = \Pr(X_t = x)$ , (and  $\pi(x)$ , the steady state probability of being at  $x$ ), we have

$$\begin{aligned} \left( \sum_{x \in \mathcal{C}} \left( \frac{p_t(x)}{\pi(x)} - 1 \right)^2 \pi(x) \right)^{1/2} &\leq (1 - \lambda_1)^t \left( \sum_{x \in \mathcal{C}} \left( \frac{p_0(x)}{\pi(x)} - 1 \right)^2 \pi(x) \right)^{1/2} \\ &\quad + \left( \frac{3}{1 - \lambda_1} \max_{x \in \mathcal{C}} \left| \frac{p_0(x)}{\pi(x)} - 1 \right| \right) \left( \frac{\pi(S)}{\pi(\bar{S})} \right)^{1/2}, \end{aligned}$$

where

$$\begin{aligned} \lambda_1^{-1} &= \max \left\{ \frac{(1 + \alpha)^3 \kappa_0 n}{\delta}, \frac{d^2}{6\delta^2} \right\} \\ &\approx \max \left( \frac{n}{4}, \frac{1}{6} \right) \left( \frac{d}{\delta} \right)^2, \end{aligned} \tag{4}$$

and the final approximate equation holds under the assumptions :  $\alpha \approx 0$  and  $2\sqrt{n}\delta/d \approx 0$ .

Further, the modified random walk satisfies the inequality with  $\lambda_1$  replaced by  $\hat{\lambda}_1$  where

$$\hat{\lambda}_1^{-1} = \nu^{-1} \frac{(1 + \alpha)^3 \kappa_0 n}{\delta}$$

where  $\nu = 1 - \frac{\delta^2}{2(1+\alpha)^3 \kappa_0 n}$ . [ $\nu \approx 1$  under the same assumptions as above.]

**Remark 1:** When  $n$  is large the term  $\tau_2 = d^2/(6\delta^2)$  in (4) is dominated by the other term. But when  $n$  is small, this may not be the case and the modified random walk will be preferable.

**Corollary 1** *Under the same conditions as in Theorem 1, we have the following bound on the variational distance:*

$$\begin{aligned} \sum_{x \in C} |p_t(x) - \pi(x)| &\leq (1 - \lambda_1)^t \left( \sum_{x \in C} \left( \frac{p_0(x)}{\pi(x)} - 1 \right)^2 \pi(x) \right)^{1/2} \\ &\quad + \left( \frac{3}{1 - \lambda_1} \max_{x \in C} \left| \frac{p_0(x)}{\pi(x)} - 1 \right| \right) \left( \frac{\pi(S)}{\pi(\bar{S})} \right)^{1/2}. \end{aligned}$$

**Proof** We have using the Cauchy-Schwartz inequality:

$$\sum_{x \in C} |p_t(x) - \pi(x)| \leq \left( \sum_{x \in C} \frac{(p_t(x) - \pi(x))^2}{\pi(x)} \right)^{1/2} \left( \sum_{x \in C} \pi(x) \right)^{1/2}.$$

The latter quantity equals the left hand side of the inequality in the Theorem and so we have the corollary. □

We first consider the body intersecting walk. Here we can apply the Theorem and its Corollary directly. The first term of the bound falls off exponentially to zero with  $t$ . The Theorem is only of use if  $\pi(S)$  is small. For any log-concave function  $F$ , we can choose a sufficiently large compact set such that the integral of  $F$  over the set is close to the integral of  $F$  over  $\mathbf{R}^n$ . If now we choose  $K$  to be somewhat larger than this set, then clearly,  $\pi(S)$  will be small. We do not quantify these observations here, because that would depend upon the properties of the specific  $F$ 's.

Let us now consider the centre point walk. We define the convex set  $K' = \{x \in K : C(x) \subseteq K\}$ , run the walk with  $C = C_C(K)$  and apply the Theorem to  $C$  and  $K'$ . This is valid as  $K' \subseteq \bigcup_{D \in C} D$  and when  $\delta$  is small  $K$  and  $K'$

will be “close” to each other. The comments in the previous paragraph are valid in this case too.

When  $K = B = B(0, R)$  we can remove the second term entirely at the expense of an extra assumption about where the distribution is concentrated. Consider the half-line  $L_u = \{ru : r \in \mathbf{R}^+\}$  where  $u \in \mathbf{R}^n$ , starting at the origin. Let  $h(r) = r^{n-1}F(ru)$  be defined on  $L_u$  and note that it is a log-concave function of  $r$ . We assume that for all  $u$  and  $r' \geq r \geq R$

$$h(0) \geq h(R) \geq h(r) \geq h(r'). \quad (5)$$

This expresses the fact that the boundary of  $B$  is located in the tails of the distribution from which we are sampling. Let  $d = 2(R + \delta)$ .

**Theorem 2** *Let  $F$  be a log-concave positive real valued function on  $\mathbf{R}^n$  satisfying (5) with  $\alpha$  satisfying (1)-(3). Consider the random walk  $X_0, X_1, \dots, X_t, \dots$  described above, with  $C = C_I(B)$  and  $5\delta \leq R$ . Then we have*

$$\left( \sum_{x \in C} \left( \frac{p_t(x)}{\pi(x)} - 1 \right)^2 \pi(x) \right)^{1/2} \leq (1 - \lambda_2)^t \left( \sum_{x \in C} \left( \frac{p_0(x)}{\pi(x)} - 1 \right)^2 \pi(x) \right)^{1/2}$$

where

$$\begin{aligned} \lambda_2^{-1} &= \max \left\{ (1 + \alpha)^3 (\kappa_0 (\kappa_1 + 1) + \kappa_2) n / \delta, \frac{d^2}{6\delta^2} \right\} \\ &\approx \frac{n}{4} \left( \frac{d}{\delta} \right)^2, \end{aligned}$$

and the final approximate equation holds under the assumptions :  $\alpha \approx 0$  and  $18\delta\sqrt{n}/d \approx 0$ .

**Corollary 2** *Under the same conditions as in Theorem 2, we have the following bound on the variational distance:*

$$\sum_{x \in C} |p_t(x) - \pi(x)| \leq (1 - \lambda_2)^t \left( \sum_{x \in C} \left( \frac{p_0(x)}{\pi(x)} - 1 \right)^2 \pi(x) \right)^{1/2}.$$

In the next section we prove a general result about the rate of convergence to the steady state for arbitrary time reversible chains. It is then a matter of estimating quantities associated with this result.

## 2 Convergence rates of time reversible chains: dealing with small sets

In the analysis of geometric random walks, it turns out that certain sets of states with relatively small steady state probabilities are not easy to analyse. In the case of random walks on convex sets, where the problem is usually discretized by using a set of cubes as the states, this problem arises for the set of  $S$  of *boundary cubes* which are those cubes in  $C$  which are not wholly contained in the convex set. This irksome problem has cost volume computation algorithms significant added complexity [2],[4] and has also led to new ideas like the use of log-concave damping functions as in [1]. In this section, we propose a general way of tackling the problem of small sets. In some sense, this serves a purpose analogous to that of  $\mu$ -conductance proposed by Lovász and Simonovits [4].

Suppose  $P$  is the  $N \times N$  transition probability matrix of an ergodic Markov Chain with  $N$  states and steady state probabilities  $\pi(\cdot)$ . We assume throughout that the chain is time-reversible, i.e., that  $\pi(x)P(x, y) = \pi(y)P(y, x)$  for

all  $x, y$ . Suppose we start the chain with initial distribution  $p_0(\cdot)$  [ i.e.,  $\Pr(X_0 = x) = p_0(x)$  for all  $x$ .] Let  $p_t(\cdot)$  be the probability distribution of  $X_t$ . We define the following quantity

$$\phi_t(x) = \frac{p_t(x)}{\pi(x)} - 1.$$

This leads to what Fill [3] calls the chi-squared distance between distributions.

To define this distance, we first define an inner product on  $\mathbf{R}^N$  by

$$\langle \phi, \psi \rangle = \sum_{x \in [N]} \phi(x)\psi(x)\pi(x)$$

and denote its associated norm by

$$|\phi|_{\pi} = \langle \phi, \phi \rangle^{1/2}.$$

We also retain the more familiar notation that  $||$  denotes Euclidean length and that  $|\phi|_{\infty} = \max\{|\phi(x)| : x \in [N]\}$ .

Suppose

$$\sigma_0 = \sup_{\substack{\phi \neq 0 \\ \pi^T \phi = 0}} \left\{ \frac{|\langle \phi, P\phi \rangle|}{\langle \phi, \phi \rangle} \right\}.$$

[From Linear Algebra and time-reversibility, it can be seen that  $P$ 's largest eigenvalue is 1 and that  $\sigma_0$  is the largest absolute value of an eigenvalue of  $P$  other than 1. We will only use the first of these facts.]

Using arguments similar to the ones used by Fill [3] to get his inequality (2.11), we can get the following inequality :

$$|\phi_t|_{\pi} \leq \sigma_0^t |\phi_0|_{\pi}.$$

So it would suffice then to prove an upper bound on  $\sigma_0$ . This, we are not always able to do for the random walk described in Section 1. But we are able to prove a bound on a quantity similar to  $\sigma_0$ , but which ignores a small set  $S$  and our aim in this section is to prove an inequality for general time-reversible chains, similar to the one above, but with the new quantity  $\sigma$  replacing  $\sigma_0$ .

Let  $S$  be an arbitrary set of states which will remain fixed for the rest of this section. Let

$$\Omega = \{\phi \in \mathbf{R}^N : \pi^T \phi = 0 \text{ and } \phi(x) = 0, x \in S\}$$

and

$$\sigma = \sup_{\substack{\phi \in \Omega \setminus \{0\} \\ \pi^T \phi = 0}} \left\{ \frac{|\langle \phi, P\phi \rangle|}{\langle \phi, \phi \rangle} \right\}.$$

The main Theorem of this section is the following :

**Theorem 3**

$$|\phi_t|_{\pi} \leq \sigma^t |\phi_0|_{\pi} + \frac{3|\phi_0|_{\infty}}{(1-\sigma)} \sqrt{\frac{\pi(S)}{\pi(\bar{S})}}. \quad (6)$$

We need some preliminary Linear Algebra. Let  $D$  denote the  $N \times N$  diagonal matrix whose  $(x, x)$ 'th entry is  $\sqrt{\pi(x)}$ . Then time reversibility is equivalent to

$$D^2 P = P^T D^2. \quad (7)$$

Let

$$Q = D P D^{-1}.$$

$Q$  has the same eigenvalues as  $P$  and equation (7) implies that it is symmetric.



$D$  “converts”  $|\cdot|_{\pi}$  to  $|\cdot|$  in a natural way. This follows from

$$\langle \phi, \psi \rangle = (D\phi)^T (D\psi)$$

for  $\phi, \psi \in \mathbf{R}^N$ . Thus

$$|\phi|_{\pi} = |D\phi| \quad \text{and} \quad \langle \phi, P\phi \rangle = (D\phi)^T Q (D\phi).$$

So using  $\psi = D\phi$  we obtain

$$\sigma = \sup_{\substack{\psi \in \tilde{\Omega} \\ \psi \neq 0}} \left\{ \left| \frac{\psi^T Q \psi}{\psi^T \psi} \right| \right\} \quad (8)$$

where

$$\tilde{\Omega} = \{ \psi : \zeta^T \psi = 0 \text{ and } \psi(x) = 0, x \in S \}$$

and  $\zeta(x) = \sqrt{\pi(x)}$  for  $x \in [N]$ . Let  $A$  denote the orthogonal projection of  $\mathbf{R}^N$  to  $\tilde{\Omega}$ . It is easy to see that  $A$  is defined by

$$A\psi(x) = \begin{cases} \psi(x) - \frac{\sqrt{\pi(x)}}{\pi(\bar{S})} \left( \sum_{y \in \bar{S}} \psi(y) \sqrt{\pi(y)} \right) & x \in \bar{S}, \\ 0 & x \in S. \end{cases}$$

**Lemma 1** *Let  $Q, \tilde{\Omega}, A, \sigma$  be as above. Then*

$$|AQA\phi| \leq \sigma |\phi|, \quad \text{for all } \phi \in \mathbf{R}^N.$$

**Proof** For  $\phi \in \tilde{\Omega}$ , we have  $\phi^T Q \phi = \phi^T AQA\phi$ . So,

$$\sigma = \sup_{\substack{\phi \in \tilde{\Omega} \\ \phi \neq 0}} \left\{ \left| \frac{\phi^T AQA\phi}{\phi^T \phi} \right| \right\} \leq \sup_{\substack{\phi \in \mathbf{R}^N \\ \phi \neq 0}} \left\{ \left| \frac{\phi^T AQA\phi}{\phi^T \phi} \right| \right\} = \sigma_1$$

where  $\sigma_1$  is the largest eigenvalue of the symmetric matrix  $B = AQA$ . (From standard Linear Algebra, if  $\tilde{\Omega} = \{x : x = Cy\}$ , where  $C$  is a matrix with independent columns, then  $A = C(C^T C)^{-1} C^T$  and is therefore symmetric.) But if  $\phi$  is a corresponding eigenvector of  $B$  then  $B\phi = \sigma_1 \phi$  implies that  $\phi \in \tilde{\Omega}$ . Hence  $\sigma = \sigma_1$  and the lemma follows.  $\square$

**Lemma 2**  $\zeta^T \psi = 0$  implies

$$|\psi - A\psi| \leq |D^{-1}\psi|_\infty \sqrt{\frac{\pi(S)}{\pi(\bar{S})}}.$$

**Proof** Assume  $\zeta^T \psi = 0$ . Let  $\psi' = \psi - A\psi$ ;  $\phi = D^{-1}\psi$ ; and  $M = |\phi|_\infty$ . Then

$$\begin{aligned} \sum_{x \in [N]} \psi'(x)^2 &= \sum_{x \in S} \psi(x)^2 + \frac{1}{\pi(\bar{S})^2} \sum_{x \in \bar{S}} \left( \sum_{y \in \bar{S}} \psi(y) \sqrt{\pi(y)} \right)^2 \pi(x) \\ &= \sum_{x \in S} \phi(x)^2 \pi(x) + \frac{1}{\pi(\bar{S})^2} \sum_{x \in \bar{S}} \pi(x) \left( \sum_{y \in \bar{S}} \phi(y) \pi(y) \right)^2 \\ &\leq M^2 \pi(S) + M^2 \pi(S)^2 / \pi(\bar{S}) \\ &= M^2 \pi(S) / \pi(\bar{S}). \end{aligned}$$

□

We now go back to the proof of the main theorem of the section, Theorem 3.

**Proof**(of Theorem 3) Let  $\psi_t = D\phi_t$ . Observe that  $|\phi|_\pi = |\psi|$ . We will prove that

$$|\psi_{t+1}| \leq \sigma |\psi_t| + 3|\phi_0|_\infty \sqrt{\frac{\pi(S)}{\pi(\bar{S})}}, \quad (9)$$

from which we get by induction on  $t$ ,

$$\begin{aligned} |\psi_t| &\leq \sigma^t |\psi_0| + 3|\phi_0|_\infty \left( \frac{1 - \sigma^{t+1}}{1 - \sigma} \right) \sqrt{\frac{\pi(S)}{\pi(\bar{S})}} \\ &\leq \sigma^t |\psi_0| + 3 \frac{|\phi_0|_\infty}{1 - \sigma} \sqrt{\frac{\pi(S)}{\pi(\bar{S})}} \end{aligned}$$

as desired. Now

$$\zeta^T \psi_t = \sum_{x \in [N]} (p_t(x) - \pi(x)) = 0$$

Also, using time-reversibility, we get,

$$(P\phi_t)(x) = \sum_{y \in [N]} \frac{P(x,y)p_t(y)}{\pi(y)} - 1 = \sum_{y \in [N]} \frac{P(y,x)p_t(y)}{\pi(x)} - 1 = \phi_{t+1}(x).$$

Thus  $P\phi_t = \phi_{t+1}$  and pre-multiplying by  $D$ , we get

$$\psi_{t+1} = Q\psi_t \text{ for } t \geq 0.$$

To prove (9), we proceed as follows :

$$|\psi_{t+1}| = |Q\psi_t| \leq |QA\psi_t| + |Q(\psi_t - A\psi_t)|.$$

Using the fact that  $Q$ 's eigenvalues have absolute value at most 1, and Lemma 2, along with the fact that  $|\phi_{t+1}|_\infty \leq |\phi_t|_\infty$  (since  $P$  has row sums equal to 1), we have,

$$|Q(\psi_t - A\psi_t)| \leq |\psi_t - A\psi_t| \leq |\phi_0|_\infty \sqrt{\frac{\pi(S)}{\pi(\bar{S})}}.$$

Now we need to bound  $|QA\psi_t|$ . But,

$$|QA\psi_t| = |AQA\psi_t| + |QA\psi_t - AQA\psi_t|.$$

We have by Lemma 1 that  $|AQA\psi_t| \leq \sigma|\psi_t|$ . So it now suffices to prove that

$$|QA\psi_t - AQA\psi_t| \leq 2|\phi_0|_\infty \sqrt{\frac{\pi(S)}{\pi(\bar{S})}}.$$

Now,

$$\begin{aligned}
|QA\psi_t - A(QA\psi_t)| &= |(I - A)QA\psi_t| \\
&\leq |(I - A)Q\psi_t| + |(I - A)Q(A\psi_t - \psi_t)| \\
&\leq |(I - A)\psi_{t+1}| + |A\psi_t - \psi_t|
\end{aligned}$$

since  $Q$  has all eigenvalues of absolute value at most 1 and also for all vectors  $v$ ,  $|(I - A)v| \leq |v|$ , because  $A$  is a projection. Each of the last two quantities is at most  $|\phi_0|_\infty \sqrt{\frac{\pi(S)}{\pi(S)}}$ , by Lemma 2. This finishes the proof of the Theorem.  $\square$

Our aim is to prove an upper bound on

$$\sigma = \sup_{\substack{\phi \in \Omega \setminus \{0\} \\ \pi^T \phi = 0}} \left\{ \frac{|\langle \phi, P\phi \rangle|}{\langle \phi, \phi \rangle} \right\}$$

for the case of the walk of Section 1. We will split the task into two parts. In the next section, we prove that for any  $\phi$  in  $\Omega \setminus \{0\}$  with  $\pi^T \phi = 0$ , we have

$$\frac{\langle \phi, P\phi \rangle}{\langle \phi, \phi \rangle} \geq - \left( 1 - \frac{\delta^2}{6d^2} \right). \quad (10)$$

Clearly for this it suffices to consider the  $\phi$  satisfying  $\langle \phi, P\phi \rangle < 0$ . Then in the ensuing section, we prove the more difficult bounds :

$$\frac{\langle \phi, P\phi \rangle}{\langle \phi, \phi \rangle} \leq 1 - \lambda,$$

where  $\lambda = \lambda_1$  (Theorem 1) or  $\lambda = \lambda_2$  (Theorem 2).

### 3 Proof of (10) - $\langle \phi, P\phi \rangle < 0$

We now return to the specific chain corresponding to our random walk. The following lemma considers the case where  $\langle \phi, P\phi \rangle$  is negative.

**Lemma 3**  $\phi \in \Omega$  implies

$$\langle \phi, P\phi \rangle \geq -(1 - \tau)\langle \phi, \phi \rangle$$

where  $\tau = \delta^2/6d^2$ .

**Proof** Consider

$$\begin{aligned} \langle \phi, P\phi \rangle + (1 - \tau)\langle \phi, \phi \rangle &= \\ \sum_{x \in C} \left( \sum_{y \in C} P(x, y)\phi(y) \right) \phi(x)\pi(x) + \sum_{x \in C} (1 - \tau)\phi(x)^2\pi(x) &= \\ \sum_{x \in C} \sum_{y \neq x} P(x, y)\phi(y)\phi(x)\pi(x) + \sum_{x \in C} (1 - P(x, x))\phi(x)^2\pi(x) + \sum_{x \in C} (2P(x, x) - \tau)\phi(x)^2\pi(x) &= \\ \sum_{x \in C} \sum_{y \neq x} (P(x, y)\phi(y)\phi(x)\pi(x) + P(x, y)\phi(x)^2\pi(x)) + \sum_{x \in C} (2P(x, x) - \tau)\phi(x)^2\pi(x) &= \\ \sum_{\{x, y\} \in E} \pi(x)P(x, y)(\phi(x) + \phi(y))^2 + \sum_{x \in C} (2P(x, x) - \tau)\phi(x)^2\pi(x), & \quad (11) \end{aligned}$$

where  $E = \{\{x, y\} : P(x, y) > 0\}$  and the last equation follows by time-reversibility.

Suppose next that the walk is at  $x \in C$ . Let  $P_i(x, x)$  denote the probability that the  $i$ 'th direction is chosen and that no movement is made at the current iteration. Thus

$$P_i(x, x) = \frac{1}{2n} \left( 1 - \min \left\{ 1, \frac{\pi(x + e_i)}{\pi(x)} \right\} + 1 - \min \left\{ 1, \frac{\pi(x - e_i)}{\pi(x)} \right\} \right)$$

and of course

$$P(x, x) = \sum_{i=1}^n P_i(x, x).$$

We will show for each  $i, i = 1, 2 \dots n$ , that with  $E_i = \{(x, y) \in E : x - y = \pm \delta e_i\}$ ,

$$\sum_{\{x,y\} \in E_i} \pi(x)P(x,y)(\phi(x)+\phi(y))^2 + \sum_{x \in C} \left(2P_i(x,x) - \frac{\tau}{n}\right) \phi(x)^2 \pi(x) \geq 0. \quad (12)$$

Fix  $i$  and consider the lines in  $\mathbf{R}^n$  parallel to  $e_i$  which go through the centres  $C$  of the cubes  $\mathcal{C}$ . These lines induce a natural partition of  $C$  into  $\mathcal{L}_i$  where each  $L \in \mathcal{L}_i$  is the set of cube centres lying on some line. Now fix  $L \in \mathcal{L}_i$  and suppose that

$$\begin{aligned} L &= \{x, x + e_i, x + 2e_i, \dots, x + se_i\} \\ &= \{x^{(0)}, x^{(1)}, \dots, x^{(s)}\}. \end{aligned}$$

We break  $L$  into *maximal* contiguous segments  $L_1, L_2, \dots$  of the form

$$\{x^{(k)}, x^{(k+1)}, \dots, x^{(\ell)}\}$$

such that

$$\pi(x^{(r+1)}) \geq \pi(x^{(r)}) \left(1 - \frac{\delta}{d}\right)$$

for  $r = k, k+1, \dots, \ell-1$ .

(A segment ends when  $\pi(x^{(\ell+1)}) < \pi(x^{(\ell)}) \left(1 - \frac{\delta}{d}\right)$ , which includes  $\ell = s$  as then the “next” cube centre has  $\pi(\cdot) = 0$ .)

Thus

$$P(x^{(r)}, x^{(r+1)}) \geq \frac{1}{2n} \left(1 - \frac{\delta}{d}\right), \quad r = k, k+1, \dots, \ell-1, \quad (13)$$

and,

$$\pi(x^{(r)}) \geq \theta \pi(x^{(r')}), \quad k \leq r' \leq r \leq \ell, \quad (14)$$

where  $\theta = \left(1 - \frac{\delta}{d}\right)^{(d/\delta)-1}$ .

Finally,

$$P_i(x^{(\ell)}, x^{(\ell)}) \geq \frac{1}{2n} \frac{\delta}{d}. \quad (15)$$

We prove (12) by showing that

$$\sum_{r=k}^{\ell-1} \pi(x^{(r)}) P(x^{(r)}, x^{(r+1)}) (\phi(x^{(r)}) + \phi(x^{(r+1)}))^2 + \sum_{r=k}^{\ell} \left( 2P_i(x^{(r)}, x^{(r)}) - \frac{\tau}{n} \right) \phi(x^{(r)})^2 \pi(x^{(r)}) \geq 0. \quad (16)$$

Now for  $k \leq r < \ell$ ,

$$\phi(x^{(r)}) = (\phi(x^{(r)}) + \phi(x^{(r+1)})) - (\phi(x^{(r+1)}) + \phi(x^{(r+2)})) + \dots \pm (\phi(x^{(\ell-1)}) + \phi(x^{(\ell)})) \pm \phi(x^{(\ell)}).$$

Applying the Cauchy-Schwartz inequality twice, we get

$$\begin{aligned} \phi(x^{(r)})^2 \pi(x^{(r)}) &\leq 2\pi(x^{(r)}) \left( \sum_{r'=r}^{\ell-1} |\phi(x^{(r')}) + \phi(x^{(r'+1)})| \right)^2 + 2\phi(x^{(\ell)})^2 \pi(x^{(r)}) \\ &\leq 2(\ell-r)\pi(x^{(r)}) \sum_{r'=r}^{\ell-1} (\phi(x^{(r')}) + \phi(x^{(r'+1)}))^2 + 2\phi(x^{(\ell)})^2 \pi(x^{(r)}) \\ &\leq 4\theta^{-1} \left( 1 - \frac{\delta}{d} \right)^{-1} n(\ell-r) \sum_{r'=r}^{\ell-1} \pi(x^{(r')}) P(x^{(r')}, x^{(r'+1)}) (\phi(x^{(r')}) + \phi(x^{(r'+1)}))^2 \\ &\quad + 2\theta^{-1} \phi(x^{(\ell)})^2 \pi(x^{(\ell)}). \end{aligned}$$

Summing over  $r = k, k+1, \dots, \ell-1$  and adding  $\phi(x^{(\ell)})^2 \pi(x^{(\ell)})$ , we obtain

$$\begin{aligned} \sum_{r=k}^{\ell} \phi(x^{(r)})^2 \pi(x^{(r)}) &\leq 2\theta^{-1} \left( 1 - \frac{\delta}{d} \right)^{-1} n \left( \frac{d}{\delta} \right)^2 \sum_{r=k}^{\ell-1} \pi(x^{(r)}) P(x^{(r)}, x^{(r+1)}) (\phi(x^{(r)}) + \phi(x^{(r+1)}))^2 \\ &\quad + \left( 1 + 2\theta^{-1} \frac{d}{\delta} \right) \phi(x^{(\ell)})^2 \pi(x^{(\ell)}). \end{aligned}$$

Comparing this with what we want i.e.(16) we see that the following suffices:

$$2\theta^{-1} \left( 1 - \frac{\delta}{d} \right)^{-1} \frac{\tau}{n} \left( \frac{d}{\delta} \right)^2 n \leq 1$$

and

$$\frac{\tau}{n} \left( 1 + 2\theta^{-1} \frac{d}{\delta} \right) \leq 2P_i(x^{(\ell)}, x^{(\ell)}).$$

Under the assumption that  $10\delta \leq d$ , we get that  $\tau = \delta^2/6d^2$  satisfies the inequalities since we have (15).

□

**Remark 2:** The modified walk has  $P(x, x) \geq 1 - \nu$  and the argument can be stopped at (11) provided  $\tau \leq 2(1 - \nu)$ . We thus need  $\nu \geq 1 - \hat{\lambda}_1/2$  in the modified walk. Note that we have  $\hat{\lambda}_1$  rather than  $\lambda_1$  as the modification introduces a factor of  $\nu$  into our eigenvalue estimate - see Remark 3.

## 4 Reduction to a continuous problem

We first introduce the quantity

$$E(\phi, \phi) = \langle \phi, \phi \rangle - \langle \phi, P\phi \rangle$$

for all  $\phi \in \mathbf{R}^C$ . The time reversibility of  $P$  allows us to conclude

$$2E(\phi, \phi) = \sum_{x \in C} \sum_{y \in \Gamma(x)} (\phi(x) - \phi(y))^2 \pi(x) P(x, y) \quad (17)$$

where  $\Gamma(x) = \{y \in C : P(x, y) > 0\}$ .

To prove (17) write

$$\begin{aligned} & \sum_{x \in C} \sum_{y \in C} \pi(x) P(x, y) (\phi(x) - \phi(y))^2 = \\ & \sum_{x \in C} \pi(x) \phi(x)^2 \sum_{y \in C} P(x, y) + \sum_{y \in C} \pi(y) \phi(y)^2 \sum_{x \in C} P(y, x) - 2 \sum_{x \in C} \pi(x) \phi(x) \sum_{y \in C} P(x, y) \phi(y). \end{aligned}$$



In this notation we must now prove that

$$\inf_{\phi \in \Omega} \frac{E(\phi, \phi)}{\langle \phi, \phi \rangle} \geq \lambda.$$

Let  $1_C$  denote the  $C$ -vector of 1's,  $\bar{\phi} = \sum \pi(x)\phi(x)$  and let  $\tilde{\Omega} = \{\phi : \phi(x) = \bar{\phi} \text{ for } x \in S\}$ . If  $\phi \in \tilde{\Omega}$  then  $\phi - \bar{\phi}1_C \in \Omega$ . Also for all  $\phi \in \mathbf{R}^N$  and for all  $z \in \mathbf{R}$ , we have

$$\begin{aligned} E(\phi - z1_N, \phi - z1_N) &= E(\phi, \phi). \\ \langle \phi - \bar{\phi}1_C, \phi - \bar{\phi}1_C \rangle &= \langle \phi, \phi \rangle - \bar{\phi}^2 \end{aligned}$$

and so we can re-define our objective as proving

$$\inf_{\substack{\phi \in \tilde{\Omega} \\ \text{non-constant}}} \frac{E(\phi, \phi)}{\langle \phi, \phi \rangle - \bar{\phi}^2} \geq \lambda. \quad (18)$$

For the rest of this section, we fix a particular non-constant  $\phi$  in  $\tilde{\Omega}$ . Let  $T = \bigcup_{x \in C} C(x)$  which is "slightly" bigger than  $K$ . Define  $\tilde{F} : T \rightarrow \mathbf{R}$  as follows: suppose  $\xi \in C(x)$  for some  $x \in C$ .  $\tilde{F}(\xi) = \bar{F}(x)$  if  $\xi \notin \partial C(x)$  and  $\tilde{F}(\xi) = 0$  otherwise.

Given  $\phi \in \mathbf{R}^N$  and a small  $\epsilon > 0$  we define  $\Phi_\epsilon : T \rightarrow \mathbf{R}$  as follows: suppose  $z \in C(x)$  for some  $x \in C$ . Let  $C(x, \epsilon)$  denote the cube centred at  $x$  with side  $\delta - 2\epsilon$ . If  $z \in C(x, \epsilon)$  we let  $\Phi_\epsilon(z) = \phi(x)$ . If  $z \notin C(x, \epsilon)$  let  $D$  be a face of  $C(x)$  which is closest to  $z$ . (If there is a tie for  $D$ , the value of  $\Phi_\epsilon$  does not matter, as we will see.) Suppose first that  $D = C(x) \cap C(y)$  for some  $y \in C$  and that  $\text{dist}(z, D) = \eta\epsilon$  where  $0 \leq \eta < 1$ . In this case we let  $\Phi_\epsilon(z) = ((1 + \eta)\phi(x) + (1 - \eta)\phi(y))/2$ . In this way, if we start at a point on a face of  $C(x, \epsilon)$  parallel to  $D$  and move towards  $D$  then  $\Phi_\epsilon$  changes linearly from  $\phi(x)$  to  $\phi(y)$  over a distance  $2\epsilon$ . Finally, if the hypercube on the other side of  $D$  to  $C(x)$  is not in  $C$  then we keep  $\Phi_\epsilon(z) = \phi(x)$ .

Let

$$I_\epsilon = \int_T |\nabla \Phi_\epsilon(z)|^2 \tilde{F}(z) dz.$$

$\Phi_\epsilon$  is not differentiable on a set  $Z$  of measure zero (consisting of points for which there is a tie for  $D$ ). We can however easily “smooth out”  $\Phi_\epsilon$  close to  $Z$  so that (17) and (1) imply

$$\begin{aligned} \epsilon I_\epsilon &= \delta^{n-1} \sum_{x \in C} \sum_{y \in \Gamma(x)} \left( \frac{\phi(x) - \phi(y)}{2} \right)^2 \bar{F}(x) + O(\epsilon) \\ &\leq \left( \frac{1 + \alpha}{4} \right) \delta^{n-1} \sum_{x \in C} \sum_{y \in \Gamma(x)} (\phi(x) - \phi(y))^2 \min\{\bar{F}(x), \bar{F}(y)\} + O(\epsilon) \\ &= (1 + \alpha) \Delta n \delta^{n-1} E(\phi, \phi) + O(\epsilon), \end{aligned}$$

where the hidden constant in  $O(\epsilon)$  may depend on  $n, F, \phi$ .

**Remark 3:** for the modified walk we need a factor of  $\nu^{-1}$  in order to get the final equation.

On the other hand, the concavity of  $\ln F$  implies that it is continuous; so for small enough  $\epsilon$ , we have  $\int_S F(\zeta) d\zeta \leq (1 + f(\epsilon)) \int_{C(x) \cap C(y)} F(\zeta) d\zeta$  where  $S$  is obtained by translating  $C(x) \cap C(y)$  towards  $x$  by some  $\epsilon' \in [0, \epsilon]$  and  $f$  is some function with  $\limsup_{\epsilon \rightarrow 0} f(\epsilon) = 0$ . This along with (2) implies that

$$\epsilon I_\epsilon \geq (1 + f(\epsilon))^{-1} (1 + \alpha)^{-1} \epsilon \int_T |\nabla \Phi_\epsilon(z)|^2 F(z) dz - O(\epsilon).$$

So

$$E(\phi, \phi) \geq \frac{\epsilon \int_T |\nabla \Phi_\epsilon(z)|^2 F(z) dz}{(1 + \alpha)^2 (1 + f(\epsilon)) n \delta^{n-1} \Delta} - O(\epsilon). \quad (19)$$

This deals with the numerator in (18). For the denominator

$$\langle \phi, \phi \rangle - \bar{\phi}^2 = \Delta^{-1} \sum_{x \in C} \phi(x)^2 \bar{F}(x) - \bar{\phi}^2$$

$$= \Delta^{-1} \sum_{x \in C} (\phi(x) - \zeta)^2 \bar{F}(x) - (\bar{\phi} - \zeta)^2 \quad \text{for any } \zeta \in \mathbf{R}. \quad (20)$$

We will use the above with  $\zeta = \mu$  where

$$\mu = \frac{\int_K \Phi_\epsilon(z) F(z) dz}{\int_K F(z) dz} \quad \text{and then let } \psi(z) = \Phi_\epsilon(z) - \mu.$$

We will show in Section 5 that

$$\int_K \psi(z)^2 F(z) dz \leq \epsilon \kappa_0 \int_K |\nabla \psi|^2 F(z) dz \quad (21)$$

and in Section 7 (for use in Theorem 2)

$$\int_{T \setminus B} \psi(z)^2 F(z) dz \leq \kappa_1 \int_B \psi(z)^2 F(z) dz + \epsilon \kappa_2 \int_T |\nabla \psi|^2 F(z) dz. \quad (22)$$

Consider first Theorem 1. It follows from (20) that

$$\begin{aligned} \langle \phi, \phi \rangle - \bar{\phi}^2 &= \Delta^{-1} \sum_{x \in C \setminus S} (\phi(x) - \mu)^2 \bar{F}(x) + \Delta^{-1} \sum_{x \in S} (\phi(x) - \mu)^2 \bar{F}(x) - (\bar{\phi} - \mu)^2 \\ &\leq \frac{1 + \alpha}{\delta^n \Delta} \int_K \psi(z)^2 F(z) dz + O(\epsilon) \end{aligned} \quad (23)$$

since  $\phi = \bar{\phi}$  for  $x \in S$ .

Thus, by (21),

$$\begin{aligned} \langle \phi, \phi \rangle - \bar{\phi}^2 &\leq \frac{1 + \alpha}{\delta^n \Delta} \epsilon \kappa_0 \int_K |\nabla \psi(z)|^2 F(z) dz + O(\epsilon) \\ &\leq \frac{1 + \alpha}{\delta^n \Delta} \epsilon \kappa_0 (\epsilon^{-1} (1 + \alpha)^2 (1 + f(\epsilon)) n \delta^{n-1} \Delta) E(\phi, \phi) + O(\epsilon) \end{aligned} \quad (24)$$

The second inequality comes from (19) and  $K \subseteq T$ . Now, (24) is true for all  $\epsilon > 0$  and so (18) follows in the case of Theorem 1.

Now consider Theorem 2. It follows from (20) that

$$\begin{aligned}
\langle \phi, \phi \rangle - \bar{\phi}^2 &\leq \frac{1+\alpha}{\delta^n \Delta} \int_T (\Phi_\epsilon(z) - \mu)^2 F(z) dz + O(\epsilon) \\
&= \frac{1+\alpha}{\delta^n \Delta} \left( \int_B \psi^2 F(x) dx + \int_{T \setminus B} \psi^2 F(z) dz \right) + O(\epsilon) \\
&\leq \frac{1+\alpha}{\delta^n \Delta} \left( (\kappa_1 + 1) \int_B \psi^2 F(z) dz + \epsilon \kappa_2 \int_T |\nabla \Phi_\epsilon(x)|^2 F(z) dz \right) + O(\epsilon) \\
&\leq \frac{1+\alpha}{\delta^n \Delta} (\kappa_0(\kappa_1 + 1) + \kappa_2) \epsilon \int_T |\nabla \Phi_\epsilon(z)|^2 F(z) dz + O(\epsilon) \\
&\leq \frac{1+\alpha}{\delta^n \Delta} (\kappa_0(\kappa_1 + 1) + \kappa_2) \epsilon (\epsilon^{-1} (1+\alpha)^2 (1+f(\epsilon)) n \delta^{n-1} \Delta) E(\phi, \phi) + O(\epsilon).
\end{aligned}$$

This true for all  $\epsilon > 0$  and so (18) follows for the case of Theorem 2.

## 5 Proof of (21)

We will reduce the geometry to one dimension by applying the following *localisation lemma* of Lovász and Simonovits [5]:

**Lemma 4** *Let  $f_1, f_2$  be upper semi-continuous functions defined on  $\mathbf{R}^n$  such that*

$$\int_{\mathbf{R}^n} f_i(z) dz > 0 \quad i = 1, 2.$$

*Then there exist  $a, b \in \mathbf{R}^n$  and a linear function  $\ell : [0, 1] \rightarrow \mathbf{R}_+$  such that*

$$\int_{t=0}^1 f(ta + (1-t)b) \ell(t)^{n-1} dt > 0, \quad i = 1, 2.$$

To apply this we replace (21) by the equivalent

$$\int_K \Phi_\epsilon^2(z) F(z) dz - \frac{(\int_K \Phi_\epsilon(z) F(z) dz)^2}{\int_K F(z) dz} \leq \epsilon \kappa_0 \int_K |\nabla \Phi_\epsilon(z)|^2 F(z) dz. \quad (25)$$

Adding a constant to  $\Phi_\epsilon$  does not change either side of this inequality and so we can assume that  $\Phi_\epsilon(z)$  is positive on  $K$ . We then use the fact that under this assumption (25) *fails* to hold if and only if there exists  $\alpha > 0$  such that

$$\int_K \Phi_\epsilon^2(z)F(z)dz - \alpha \int_K \Phi_\epsilon(z)F(z)dz > \epsilon\kappa_0 \int_K |\nabla\Phi_\epsilon(z)|^2 F(z)dz$$

and

$$-\int_K \Phi_\epsilon(z)F(z)dz + \alpha \int_K F(z)dz > 0.$$

We apply Lemma 4 with

$$f_1 = (\Phi_\epsilon^2 F - \alpha\Phi_\epsilon F - \epsilon\kappa_0 |\nabla\Phi_\epsilon(x)|^2 F)\chi_K$$

and

$$f_2 = (-\Phi_\epsilon F + \alpha F)\chi_K.$$

( $\chi_K$  is the indicator function of the body  $K$ .)

Let  $a, b, \ell$  be as in the lemma. We observe that we can take  $a, b \in K$  because of the factor  $\chi_K$ . Let  $g(t) = \Phi_\epsilon((1-t)a + tb)$ ,  $h(t) = F((1-t)a + tb)\ell(t)^{n-1}$ ,  $\pi(t) = h(t)/\int_{\xi=0}^1 h(\xi)d\xi$  and  $\tilde{g}(t) = |\nabla\Phi_\epsilon((1-t)a + tb)|$ . Note that  $\pi(t)$  is log-concave.

We then see that if (25) fails to hold then

$$\int_{t=0}^1 g(t)^2 \pi(t) dt - \left( \int_{t=0}^1 g(t) \pi(t) \right)^2 \leq \epsilon\kappa_0 \int_{t=0}^1 \tilde{g}(t)^2 \pi(t) dt \quad (26)$$

fails to hold.

We can thus prove (21) by proving (26). We replace the LHS of (26) using the identity

$$\int_{t=0}^1 g(t)^2 \pi(t) dt - \left( \int_{t=0}^1 g(t) \pi(t) \right)^2 = \frac{1}{2} \int_{s=0}^1 \int_{t=0}^1 (g(t) - g(s))^2 \pi(s) \pi(t) ds dt. \quad (27)$$

Let  $\hat{d} = |b - a|$  and  $u = (b - a)/\hat{d}$ . Then for  $0 \leq s \leq t \leq 1$ ,

$$\begin{aligned} (g(t) - g(s))^2 &= \left( \int_{\xi=s}^t g'(\xi) d\xi \right)^2 \\ &= \hat{d}^2 \left( \int_{\xi=s}^t \sum_{j=1}^n u_j \chi_j(\xi) \frac{\partial \Phi_\epsilon}{\partial x_j} ((1 - \xi)a + \xi b) d\xi \right)^2, \end{aligned}$$

where  $\chi_j(\cdot)$  is defined by

$$\chi_j(\xi) = \begin{cases} 1 & \text{if } \frac{\partial \Phi_\epsilon}{\partial x_j} ((1 - \xi)a + \xi b) \neq 0 \\ 0 & \text{otherwise.} \end{cases}$$

By the Cauchy-Schwartz inequality, we have

$$\sum_{j=1}^n |u_j \chi_j(\xi) \frac{\partial \Phi_\epsilon}{\partial x_j} ((1 - \xi)a + \xi b)| \leq \left( \sum_{j=1}^n u_j^2 \chi_j(\xi) \right)^{1/2} \tilde{g}(\xi).$$

So we get with another application of Cauchy-Schwartz,

$$\begin{aligned} (g(t) - g(s))^2 &\leq \hat{d}^2 \left( \int_{\xi=s}^t \left( \sum_{j=1}^n u_j^2 \chi_j(\xi) \right)^{1/2} \tilde{g}(\xi) d\xi \right)^2 \\ &\leq \hat{d}^2 \left( \int_{\xi=s}^t \sum_{j=1}^n u_j^2 \chi_j(\xi) d\xi \right) \left( \int_{\xi=s}^t \tilde{g}(\xi)^2 d\xi \right). \end{aligned}$$

Now each time the line from  $s$  to  $t$  crosses a hyperplane of the form  $x_j = m\delta$ ,  $m$  an integer, we get a contribution of  $2\epsilon/\hat{d}u_j$  to  $\int \chi_j(\xi) d\xi$ . Furthermore, the number of such crossings is at most

$$\frac{\hat{d}u_j(t - s)}{\delta} + 1. \quad (28)$$

So we get (using the facts that  $\sum_{j=1}^n u_j^2 = 1$  and  $\sum |u_j| \leq \sqrt{n}$ )

$$(g(t) - g(s))^2 \leq 2\hat{d}^2\epsilon \left( \frac{t - s}{\delta} + \frac{\sqrt{n}}{\hat{d}} \right) \int_{\xi=s}^t \tilde{g}(\xi)^2 d\xi.$$

Thus if RHS(27) denotes the RHS of (27) then

$$\begin{aligned}
\text{RHS(27)} &\leq \hat{d}^2 \epsilon \int_{s=0}^1 \int_{t=0}^1 \left( \frac{t-s}{\delta} + \frac{\sqrt{n}}{\hat{d}} \right) \int_{\xi=s}^t \tilde{g}(\xi)^2 d\xi \pi(t) \pi(s) dt ds \\
&= 2\hat{d}^2 \epsilon \int_{\xi=0}^1 \tilde{g}(\xi)^2 \pi(\xi) \left( \int_{s=0}^{\xi} \int_{t=\xi}^1 \left( \frac{t-s}{\delta} + \frac{\sqrt{n}}{\hat{d}} \right) \frac{\pi(s)\pi(t)}{\pi(\xi)} dt ds \right) d\xi
\end{aligned} \tag{29}$$

where the last equation is obtained by interchanging the order of integration, the factor of 2 coming from the fact that  $s, t$  are interchangeable in the previous expression. Now let

$$\Pi = \{ \pi \in [0, 1] \rightarrow \mathbf{R}_+ : \pi \text{ is log-concave and } \int_{t=0}^1 \pi(t) dt = 1 \}.$$

Let

$$M_1 = \sup_{\substack{\pi \in \Pi \\ \xi \in [0,1]}} \int_{s=0}^{\xi} \int_{t=\xi}^1 (t-s) \frac{\pi(s)\pi(t)}{\pi(\xi)} dt ds$$

and

$$M_2 = \sup_{\substack{\pi \in \Pi \\ \xi \in [0,1]}} \int_{s=0}^{\xi} \int_{t=\xi}^1 \frac{\pi(s)\pi(t)}{\pi(\xi)} dt ds.$$

Then (29) implies

$$\text{RHS(27)} \leq 2\hat{d}^2 \epsilon \left( \frac{M_1}{\delta} + \frac{M_2 \sqrt{n}}{\hat{d}} \right) \int_{\xi=0}^1 \tilde{g}(\xi)^2 \pi(\xi) d\xi. \tag{30}$$

We will prove below that

$$M_1 = \frac{1}{8} \text{ and } M_2 = \frac{1}{4}$$

and (21) follows immediately from (30).

## 6 Computation of $M_1$ and $M_2$

We begin with  $M_1$ . Rather than restrict  $\pi \in \Pi$  we prove that if  $h : [0, 1] \rightarrow \mathbf{R}_+$  is log-concave then

$$\int_{s=0}^{\xi} \int_{t=\xi}^1 (t-s)h(s)h(t)dt ds \leq \frac{h(\xi)}{8} \int_{s=0}^1 h(s)ds. \quad (31)$$

This will prove  $M_1 \leq 1/8$  which is what we want. We then note that  $h = 1$  satisfies (31) with equality.

Since  $\log h$  is concave there exists  $\alpha \in \mathbf{R}$  such that

$$h(s) \leq h(\xi)e^{\alpha(s-\xi)}, \quad s \in [0, 1]. \quad (32)$$

Our aim first is to show that the extremal  $h$  satisfies (32) with equality for all  $s \in [0, 1]$ , for some  $\alpha$ . Let

$$I_0 = \int_{s=0}^{\xi} h(s)ds \text{ and } I_1 = \int_{s=\xi}^1 h(s)ds,$$

$$J_0 = \int_{s=0}^{\xi} (\xi-s)h(s)ds \text{ and } J_1 = \int_{t=\xi}^1 (t-\xi)h(t)dt.$$

Then (31) is equivalent to

$$\frac{I_0 J_1 + I_1 J_0}{I_0 + I_1} \leq \frac{h(\xi)}{8}$$

or

$$\left( \frac{J_1}{I_1} + \frac{J_0}{I_0} \right) \frac{1}{I_0^{-1} + I_1^{-1}} \leq \frac{h(\xi)}{8}.$$

Suppose now that we fix  $\alpha$  and also  $h(\xi) = \beta > 0$ . Let  $I_0(\alpha, \beta) = \int_{s=0}^{\xi} \beta e^{\alpha(s-\xi)}$  and let  $I_1(\alpha, \beta), J_0(\alpha, \beta), J_1(\alpha, \beta)$  be defined analogously. Clearly, under these circumstances  $I_k \leq I_k(\alpha, \beta)$  for  $k = 0, 1$  and so

$$\frac{1}{I_0^{-1} + I_1^{-1}} \leq \frac{1}{I_0(\alpha, \beta)^{-1} + I_1(\alpha, \beta)^{-1}}. \quad (33)$$



We now prove that

$$\frac{J_k}{I_k} \leq \frac{J_k(\alpha, \beta)}{I_k(\alpha, \beta)} \quad k = 0, 1. \quad (34)$$

We prove (34) for  $k = 1$ , the proof for  $k = 0$  being essentially the same. Let  $M$  be a positive integer and  $\theta = (1 - \xi)/M$ . Let  $g = \log h$  and let  $g_i = g(\xi + i\theta)$ ,  $i = 0, 1, \dots, M$ . The concavity of  $g$  implies that

$$g_{i+2} - g_{i+1} \leq g_i - g_{i+1} \quad 0 \leq i < M - 2, \quad (35)$$

and (32) implies

$$g_i \leq g_0 + \alpha i \theta \quad 0 \leq i \leq M. \quad (36)$$

Now choose  $\eta > 0$  small. By choosing  $M$  sufficiently large we can ensure that

$$\frac{J_1}{I_1} \leq \frac{\sum_{i=0}^M i e^{g_i}}{\sum_{i=0}^M e^{g_i}} + \eta. \quad (37)$$

Denote the RHS of (37) by  $\rho(g_0, g_1, \dots, g_M)$ . Since  $\eta$  is arbitrary, we need only show that subject to (35),(36),  $\rho$  is maximised when  $g_i = g_0 + \alpha i \theta$  i.e.

$$\rho(g) \leq \frac{\sum_{i=0}^M i e^{g_0 + \alpha i \theta}}{\sum_{i=0}^M e^{g_0 + \alpha i \theta}}. \quad (38)$$

This is easy to do by backwards induction on

$$k = k(g) = \max\{\ell : g_i = g_0 + \alpha i \theta, 0 \leq i \leq \ell\}.$$

The base case  $k = M$  is trivial and so assume that (38) holds for  $k = \kappa + 1$  and assume that  $k = \kappa$ . Let

$$\nu = g_0 + \alpha \kappa \theta - g_\kappa > 0.$$

Define  $\bar{g}$  by

$$\bar{g}_i = \begin{cases} g_i & 0 \leq i < \kappa \\ g_i + \nu & \kappa \leq i \leq M \end{cases}$$

Note that  $\bar{g}$  satisfies (35) and (36) and that  $k(\bar{g}) = \kappa + 1$ . Hence our inductive assumption implies that  $\bar{g}$  satisfies (38). On the other hand if  $e^{\nu\theta} = 1 + \epsilon$  and  $h_i = e^{g_i}$  then

$$\begin{aligned} \rho(\bar{g}) - \rho(g) &= \frac{\sum_{i=0}^M ih_i + \epsilon \sum_{i=\kappa}^M ih_i}{\sum_{i=0}^M h_i + \epsilon \sum_{i=\kappa}^M h_i} - \frac{\sum_{i=0}^M ih_i}{\sum_{i=0}^M h_i} \\ &= \frac{\epsilon \left( \sum_{i=0}^{\kappa-1} h_i \sum_{i=\kappa}^M ih_i - \sum_{i=0}^{\kappa-1} ih_i \sum_{i=\kappa}^M h_i \right)}{\left( \sum_{i=0}^M h_i + \epsilon \sum_{i=\kappa}^M h_i \right) \sum_{i=0}^M h_i} \\ &\geq 0, \end{aligned}$$

since clearly

$$\frac{\sum_{i=\kappa}^M ih_i}{\sum_{i=\kappa}^M h_i} \geq \kappa > \frac{\sum_{i=0}^{\kappa-1} ih_i}{\sum_{i=0}^{\kappa-1} h_i}.$$

We can therefore assume from now on that  $h(s) = \beta e^{\alpha(s-\xi)}$  for some  $\alpha, \beta$ . We can in fact assume that  $\beta = 1$  as  $\beta$  contributes a factor of  $\beta^2$  to both sides of (31). So now let

$$\begin{aligned} \gamma(\alpha, \xi) &= \frac{\int_{s=0}^{\xi} \int_{t=\xi}^1 (t-s) e^{\alpha(s+t)} dt ds}{e^{\alpha\xi} \int_{s=0}^1 e^{\alpha s} ds} \\ &= \frac{e^{\alpha} + \xi - \xi e^{\alpha} - e^{\alpha(1-\xi)}}{\alpha(e^{\alpha} - 1)}. \end{aligned}$$

We must show that  $\gamma(\alpha, \xi) \leq 1/8$  for  $\alpha \in \mathbf{R}$  and  $\xi \in [0, 1]$ . Now,

$$\frac{\partial \gamma}{\partial \xi} = \frac{1}{\alpha(e^{\alpha} - 1)} (1 - e^{\alpha} + \alpha e^{\alpha(1-\xi)})$$

and

$$\frac{\partial^2 \gamma}{\partial \xi^2} = \frac{1}{\alpha(e^{\alpha} - 1)} (-\alpha^2 e^{\alpha(1-\xi)}) < 0.$$

It follows that for fixed  $\alpha$ ,  $\gamma$  is maximised when

$$\xi = \xi^* = \frac{1}{\alpha} \log \left( \frac{\alpha}{1 - e^{-\alpha}} \right).$$

Now let

$$\begin{aligned} f(\alpha) &= \gamma(\alpha, \xi^*(\alpha)) \\ &= \frac{1}{\alpha^2} \log \left( \frac{e^\alpha - 1}{\alpha} \right) - \frac{1}{\alpha^2} + \frac{1}{\alpha(e^\alpha - 1)}. \end{aligned}$$

A simple computation yields

$$\lim_{\alpha \rightarrow 0} f(\alpha) = \frac{1}{8}$$

and that  $f$  is even i.e.  $f(-\alpha) = f(\alpha)$  for all  $\alpha \in \mathbf{R}$ .

Next let

$$g(\alpha) = \alpha^2 f(\alpha) - \frac{\alpha^2}{8}.$$

Then

$$g'(\alpha) = -\frac{e^{2\alpha}(\alpha - 2)^2 + e^\alpha(2\alpha^2 - 8) + (\alpha + 2)^2}{4\alpha(e^\alpha - 1)^2}$$

By checking that the series expansion of the denominator above contains only non-negative coefficients we see that  $g'(\alpha) \leq 0$  for  $\alpha \geq 0$ . Thus  $g(\alpha) \leq g(0) = 0$  for  $\alpha \geq 0$  and since  $f$  is even this completes the proof that  $M_1 = 1/8$ .

For the computation of  $M_2$  we need to show

$$\int_{s=0}^{\xi} \int_{t=\xi}^1 h(s)h(t)dt ds \leq \frac{h(\xi)}{4} \int_{s=0}^1 h(s)ds.$$

Fixing  $h(\xi) = \beta$  and assuming (32), this amounts to

$$\frac{I_0 I_1}{I_0 + I_1} \leq \frac{\beta}{4}.$$

Thus we can once again assume that the extremal  $h$  satisfies (32) and that  $\beta = 1$ .

So now let

$$\begin{aligned}
 \zeta(\alpha, \xi) &= \frac{\int_{s=0}^{\xi} \int_{t=\xi}^1 e^{\alpha(s+t)} dt ds}{e^{\alpha\xi} \int_{s=0}^1 e^{\alpha s} ds} \\
 &= \frac{\int_{s=0}^{\xi} e^{\alpha s} ds \int_{t=\xi}^1 e^{\alpha t} dt}{e^{\alpha\xi} \int_{s=0}^1 e^{\alpha s} ds} \\
 &= \frac{(e^{\alpha\xi} - 1)(e^{\alpha} - e^{\alpha\xi})}{\alpha e^{\alpha\xi} (e^{\alpha} - 1)} \\
 &= \frac{e^{\alpha} - e^{\alpha\xi} - e^{\alpha(1-\xi)} + 1}{\alpha(e^{\alpha} - 1)}.
 \end{aligned}$$

We need to show that  $\zeta(\alpha, \xi) \leq 1/4$  for  $\xi \in [0, 1]$ . Now

$$\frac{\partial \zeta}{\partial \xi} = \frac{1}{(e^{\alpha} - 1)} (e^{\alpha(1-\xi)} - e^{\alpha\xi})$$

and

$$\frac{\partial^2 \zeta}{\partial \xi^2} = -\frac{\alpha}{(e^{\alpha} - 1)} ((e^{\alpha(1-\xi)} + e^{\alpha\xi}) < 0.$$

Thus  $\zeta(\alpha, \xi)$  is maximised at  $\xi = 1/2$ , independent of  $\alpha$ . Now let

$$f(\alpha) = \zeta(\alpha, 1/2) = \frac{(e^{\alpha/2} - 1)^2}{\alpha(e^{\alpha} - 1)}.$$

Then

$$\lim_{\alpha \rightarrow 0} f(\alpha) = 1/4$$

and if  $g(\alpha) = \alpha f(\alpha) - \alpha/4$  then

$$g'(\alpha) = -\frac{(e^{\alpha/2} - 1)^2}{4(e^{\alpha/2} + 1)^2} \leq 0.$$

This shows that  $g(\alpha) \leq g(0) = 0$  for  $\alpha \geq 0$  and  $g(\alpha) \geq g(0)$  for  $\alpha \leq 0$  and completes our proof that  $M_2 = 1/4$ .

## 7 Proof of (22)

We first observe that if  $L$  is a half-ray in  $\mathbf{R}^n$  with the origin as one endpoint then  $L \cap T$  is a segment.

We introduce polar coordinates  $(r, \theta = (\theta_1, \theta_2, \dots, \theta_{n-1}))$  so that

$$z_j = r \sin(\theta_j) \prod_{i=1}^{j-1} \cos(\theta_i), \quad j \in [n].$$

Then

$$\int_{T \setminus B} \psi(z)^2 F(z) dz = \int_{\theta} \left( \int_{r=R}^{R_1(\theta)} r^{n-1} \psi(r, \theta)^2 F(r, \theta) dr \right) J(\theta) d\theta \quad (39)$$

where  $R_1(\theta)$  is the length of the interval  $L_{\theta} \cap T$  and  $L_{\theta}$  is the half-ray in direction  $\theta$ .  $r^{n-1} J(\theta)$  is the Jacobian of the transformation. Similarly,

$$\int_B \psi(z)^2 F(z) dz = \int_{\theta} \left( \int_{r=0}^R r^{n-1} \psi(r, \theta)^2 F(r, \theta) dr \right) J(\theta) d\theta \quad (40)$$

and

$$\int_T |\nabla \psi|^2 F(z) dz = \int_{\theta} \left( \int_{r=R}^{R_1(\theta)} r^{n-1} |\nabla \psi|^2 F(r, \theta) dr \right) J(\theta) d\theta \quad (41)$$

Now consider a fixed  $\theta$ . Let  $h(r) = r^{n-1} F(r, \theta)$  and  $g(r) = \psi(r, \theta)$ . Note that  $h$  is log-concave. Let  $u$  denote the vector of Euclidean length one in the direction  $\theta$ . Then we can write

$$g'(r) = \sum_{j=1}^n u_j \chi_j \frac{\partial \psi}{\partial z_j}$$

where  $\chi_j = \chi_j(r)$  is the indicator for  $\frac{\partial \psi}{\partial z_j} \neq 0$ .

We prove

$$\int_{r=R}^{R_1} g(r)^2 h(r) dr \leq \kappa_1 \int_{r=0}^R g(r)^2 h(r) dr + \epsilon \kappa_2 \int_{r=0}^R |\nabla \psi|^2 h(r) dr, \quad (42)$$

and then (22) follows from (39), (40) and (41). So suppose that  $0 \leq \alpha \leq \zeta \leq R_1$ . Then

$$\begin{aligned} g(\zeta) - g(\alpha) &= \int_{r=\alpha}^{\zeta} g'(r) dr \\ &= \int_{r=\alpha}^{\zeta} \sum_{j=1}^n u_j \chi_j \frac{\partial \psi}{\partial z_j} \sqrt{h(r)/h(r)} dr. \end{aligned} \quad (43)$$

Hence, applying the Cauchy-Schwartz inequality twice,

$$\begin{aligned} g(\zeta) - g(\alpha) &\leq \int_{r=\alpha}^{\zeta} \left( \sum_{j=1}^n u_j^2 \chi_j^2 h(r)^{-1} \right)^{1/2} \left( \sum_{j=1}^n \left( \frac{\partial \psi}{\partial z_j} \right)^2 h(r) \right)^{1/2} dr \\ &\leq \left( \int_{r=\alpha}^{\zeta} \sum_{j=1}^n u_j^2 \chi_j^2 h(r)^{-1} dr \right)^{1/2} \left( \int_{r=\alpha}^{\zeta} |\nabla \psi|^2 h(r) dr \right)^{1/2} \end{aligned} \quad (44)$$

Now take  $\alpha = R$ . Then by assumption (5),  $\zeta \geq r \geq R$  implies  $h(\zeta) \leq h(r)$ .

Hence

$$(g(\zeta) - g(R))^2 h(\zeta) \leq L_* I_*$$

where

$$I_* = \int_0^{R_1} |\nabla \psi|^2 h(r) dr$$

and

$$L_* = \int_{r=0}^{R_1} \sum_{j=1}^n u_j^2 \chi_j dr.$$

We will estimate  $L_*$  later but first note that we have now have

$$\int_{r=R}^{R_1} (g(r) - g(R))^2 h(r) dr \leq (R_1 - R) L_* I_*$$

or equivalently

$$\int_{r=R}^{R_1} g(r)^2 h(r) dr \leq -g(R)^2 \int_{r=R}^{R_1} h(r) dr + 2g(R) \int_{r=R}^{R_1} g(r) h(r) dr + (R_1 - R) L_* I_*. \quad (45)$$

So we now estimate the middle term of the RHS of (45). From (44) we see that for  $r \geq R$

$$g(r) \leq g(R) + \left( \int_{\zeta=R}^r \sum_{j=1}^n u_j^2 \chi_j^2 h(\zeta)^{-1} d\zeta \right)^{1/2} I_*^{1/2} \quad (46)$$

and so

$$\int_{r=R}^{R_1} g(r)h(r) \leq g(R) \int_{r=R}^{R_1} h(r)dr + h(R)^{1/2}(R_1 - R)(L_*I_*)^{1/2}. \quad (47)$$

So from (45) and the above

$$\begin{aligned} \int_{r=R}^{R_1} g(r)^2 h(r)dr &\leq g(R)^2 \int_{r=R}^{R_1} h(r)dr + 2g(R)h(R)^{1/2}(R_1 - R)(L_*I_*)^{1/2} + (R_1 - R)L_*I_* \\ &\leq g(R)^2 h(R)(R_1 - R) + 2g(R)h(R)^{1/2}(R_1 - R)(L_*I_*)^{1/2} + (R_1 - R)L_*I_*. \end{aligned} \quad (48)$$

Assume now that there exists  $\eta \in [0, R]$  such that  $g(\eta) \leq g(R)/2$  ( we will remove this assumption later.) Then, from (44),

$$g(R) - g(\eta) = \int_{r=\eta}^R g'(r)dr \leq \left( \int_{r=0}^R \sum_{j=1}^n u_j^2 \chi_j^2 h(r)^{-1} dr \right)^{1/2} I_*^{1/2}.$$

and so

$$(g(R) - g(\eta))h(R)^{1/2} \leq (L_*I_*)^{1/2},$$

or

$$g(R)h(R)^{1/2} \leq 2(L_*I_*)^{1/2}. \quad (49)$$

Substituting this into (48) gives

$$\int_{r=R}^{R_1} g(r)^2 h(r)dr \leq 9(R_1 - R)L_*I_*. \quad (50)$$

This was proved assuming the existence of  $\eta$  such that  $g(\eta) \leq g(R)/2$ . But if  $g(r) \geq g(R)/2$  for  $0 \leq r \leq R$  then

$$\begin{aligned} J_* &= \int_{r=0}^R g(r)^2 h(r) dr \\ &\geq \int_{r=0}^R \frac{g(R)^2 h(R)}{4} dr \\ &= Rg(R)^2 h(R)/4. \end{aligned}$$

Substituting this into (48) gives

$$\begin{aligned} \int_{r=R}^{R_1} g(r)^2 h(r) dr &\leq 4J_*(R_1 - R)/R + 2(L_* I_* J_*/R)^{1/2}(R_1 - R) + (R_1 - R)L_* I_* \\ &= (R_1 - R) \left( \frac{4J_*}{R} + 4 \left( \frac{L_* I_* J_*}{R} \right)^{1/2} + L_* I_* \right). \end{aligned} \quad (51)$$

If  $J_*/R \leq L_* I_*$  then the RHS of (51) can be bounded by the RHS of (50). If  $J_*/R \geq L_* I_*$  then the RHS of (51) can be bounded by  $9(R_1 - R)J_*/R$ . Thus in all cases

$$\int_{r=R}^{R_1} g(r)^2 h(r) dr \leq 9(R_1 - R) \left( \frac{J_*}{R} + L_* I_* \right). \quad (52)$$

Now  $R_1 - R \leq \delta\sqrt{n}$  and for  $j \in [n]$ , (see (28)),

$$\int_{r=0}^{R_1} \chi_j dr \leq 2\epsilon \left( \frac{R_1}{\delta} + 1 \right)$$

which implies

$$L_* \leq 2\epsilon \left( \frac{R_1}{\delta} + 1 \right).$$

Inequality (42) now follows from (52).

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