

On Low Distortion Embeddings of Statistical Distance Measures into Low Dimensional Spaces*

Arnab Bhattacharya Purushottam Kar Manjish Pal

Department of Computer Science and Engineering
Indian Institute of Technology Kanpur, INDIA.

{arnabb,purushot,manjish}@cse.iitk.ac.in

Abstract

Statistical distance measures have found wide applicability in information retrieval tasks that typically involve high dimensional datasets. In order to reduce the storage space and ensure efficient performance of queries, dimensionality reduction while preserving the inter-point similarity is highly desirable. In this paper, we investigate various statistical distance measures from the point of view of discovering low distortion embeddings into low-dimensional spaces. More specifically, we consider the Mahalanobis distance measure, the Bhattacharyya class of divergences and the Kullback-Leibler divergence. We present a dimensionality reduction method based on the Johnson-Lindenstrauss Lemma for the Mahalanobis measure that achieves arbitrarily low distortion. By using the Johnson-Lindenstrauss Lemma again, we further demonstrate that the Bhattacharyya distance admits dimensionality reduction with arbitrarily low additive error. We also examine the question of embeddability into metric spaces for these distance measures due to the availability of efficient indexing schemes on metric spaces. We provide explicit constructions of point sets under the Bhattacharyya and the Kullback-Leibler divergences whose embeddings into any metric space incur arbitrarily large distortions. We show that the lower bound presented for Bhattacharyya distance is nearly tight by providing an embedding that approaches the lower bound for relatively small dimensional datasets.

1 Introduction

The problem of embedding distance measures into normed spaces arises in applications dealing with huge amounts of high-dimensional data where performing point, range or nearest-neighbor (NN) queries in the ambient space entails enormous computational costs. The prohibitive costs arise in most cases due to two factors. First, calculating pairwise distances and answering proximity queries such as k -NN queries becomes costlier as the dimensionality of the data increases (a phenomenon more commonly known by the epithet “curse of dimensionality”). Second, in many cases such as image databases, the imposed distance measures such as the earth mover’s distance [RTG00] are inherently expensive to compute. The problem of indexing and searching is magnified if the distance measures do not form a metric.

*The short version of this paper was accepted for presentation at the 20th International Conference on Database and Expert Systems Applications, DEXA 2009.

Various approaches have been proposed to solve this problem. These include obtaining easily estimable upper/lower-bounds on the distance measures [LBS06, RTG00] and finding embeddings which allow specific proximity queries to be efficiently solved [CL08, IT03]. These methods have been found to be crucial for database retrieval algorithms in obtaining speedups over naïve search techniques. This is mainly due to the fact that, in many of these examples, the lower/upper-bounds or the embeddings involve an l_p metric for which there exist efficient algorithms for answering proximity queries [Sam05].

The concept of a “low distortion” embedding (defined in Section 2) is very useful in this context. A low distortion embedding ensures that notions of distance are preserved almost intact. This is certainly most desirable since it gives performance guarantees in terms of accuracy for all proximity queries by preserving the geometry of the original space almost exactly as against many of the methods cited above which are optimized for specific types of queries. The presence of several index structures for metric spaces (especially for the Euclidean space) [Sam05] makes it natural to try to approximate a given distance measure by a metric distance (especially Euclidean distance). Getting an approximation of the original distance measure in terms of a metric distance also shows how inherently “geometric” is the distance measure. In fact if the new metric distance is l_2 , there is the added benefit of being able to drastically reduce the dimensionality of the objects in the database while incurring a very small distortion via the Johnson-Lindenstrauss lemma [JL84]. Apart from its practical importance, such a result that quantifies the relation between the distance measures is of theoretical interest as well, and results of this nature, especially when both the distance measures are metrics, have gained huge interest in theoretical computer science over the past few years [Mat02].

A more interesting, and often more difficult, situation arises in case of statistical distance measures. They are widely used in database and pattern recognition applications and typically involve high-dimensional data. It has been found that in many scenarios, especially in similarity based search in image retrieval [RBD05], statistical distance measures like the Mahalanobis [Mah36] and Bhattacharyya [Bha43] measures give better performance than the standard l_2 distance. In the field of bioinformatics, the Mahalanobis distance measure has been found to be more useful than the l_2 distance when the distance between two DNA sequences is measured by simultaneously comparing the frequencies of all subsequences of n adjacent letters (i.e., n -words) in the two sequences [WBD97]. Furthermore, the Mahalanobis distance has found application in face recognition as well [FHVW03]. The Bhattacharyya class of distance measures which include the Bhattacharyya distance and the Hellinger distance are also widely used in diverse database scenarios such as nearest-neighbor classification [LS99], detecting voice over IP floods [SWWJ08], and recognition tasks [CRM00]. However, it should be noted that often applications of the Bhattacharyya distance use the distance measure to calculate the dissimilarity between multivariate normal distributions; we do not address that in this paper. Another important and widely used statistical similarity measure is the Kullback-Leibler divergence [Kul59]. It has been shown that the Kullback-Leibler divergence is well suited for use in real-time image segmentation algorithms and time-critical texture classification and retrieval from large databases [MSB02]. It has also been used in machine learning to design pattern classifiers for high-dimensional image spaces [LS03]. Apart from its applications this measure is interesting from a theoretical perspective as well because of its information-theoretic roots.

These distance measures have received a lot of attention recently and have been examined from several perspectives including clustering [CM08], NN-retrieval [Cay08], computing Voronoi

diagrams [NBN07], and sketching [GIM07]. We examine these distance measures from another interesting perspective—that of low distortion embeddings into metric spaces and dimensionality reduction. The lack of inherent “geometric” properties make them harder candidates for low distortion and low-dimensionality embeddings into metric spaces. To the best of our knowledge, this is the first investigation into these distance measures from the point of view of dimensionality reduction and embeddability into metric spaces.

Our Contributions: In this paper, we examine three statistical distance measures with the goal of obtaining low distortion, low-dimensional embeddings for them. The paper is structured as follows. In Section 2, we provide definitions and well known results that will be used in the subsequent discussion. In Section 3, we consider the Bhattacharyya distance and prove that there cannot exist low distortion embeddings for the Bhattacharyya distance into a metric space. We develop a technique which shows that the lower bound on the distortion gets larger as we include distributions that are “farther” from the uniform distribution in the probability simplex. We also provide an embedding into the l_2^2 space (which forms a metric in the positive orthant) that approaches the lower bound for small dimensions.

In Section 4, using the technique developed in the previous section, we show a similar result for the Kullback-Leibler divergence. We also develop another technique that gives better bounds on the distortion when the set of distributions under consideration does not contain distributions that are “far away” from the uniform distribution. The section ends with a result relating the Kullback-Leibler divergence and the l_2^2 measure. Finally, in Section 5, we provide low distortion embeddings for the family of Quadratic Form Distances. As a special case, we show that the Mahalanobis metric also admits a low distortion embedding. We end the paper with some concluding remarks in Section 6.

2 Preliminaries

We begin by defining a few preliminary concepts related to metric spaces and embeddings.

Definition 1 (Metric Space). *A pair $M = (X, \rho)$ where X is a set and $\rho : X \times X \rightarrow \mathbb{R}^+ \cup \{0\}$ is called a metric space provided the distance measure ρ satisfies the properties of identity, symmetry and triangular inequality.*

Definition 2 (D -embedding and Distortion). *Given two metric spaces (X, ρ) and (Y, σ) , a mapping $f : X \rightarrow Y$ is called a D -embedding where $D \geq 1$, if there exists a number $r > 0$ such that for all $x, y \in X$,*

$$r \cdot \rho(x, y) \leq \sigma(f(x), f(y)) \leq D \cdot r \cdot \rho(x, y)$$

The infimum of all numbers D such that f is a D -embedding is called the distortion of f .

In general, the factor r is intended to allow the distances to be scaled by some constant factor and does not affect the definition of the embedding (see [Mat02] for details). It is easy to see that this notion of distortion can be naturally extended to non-metric spaces as well.

A classic result widely used in the field of metric embeddings is the Johnson-Lindenstrauss Lemma [JL84] which makes it possible for large point sets in high-dimensional Euclidean spaces to be embedded into low-dimensional Euclidean spaces with arbitrarily small distortion.

Theorem 1 (Johnson-Lindenstrauss Lemma [Mat02]). *Let X be an n -point set in a d -dimensional Euclidean space (i.e. $(X, l_2) \subset (\mathbb{R}^d, l_2)$), and let $\epsilon \in (0, 1]$ be given. Then there exists a $(1 + \epsilon)$ -embedding of X into (\mathbb{R}^k, l_2) where $k = O(\epsilon^{-2} \log n)$. Furthermore, this embedding can be found out in randomized polynomial time.*

The main idea being used here is that the length of a d -dimensional vector when randomly projected onto a lower k -dimensional space is sharply concentrated around its expected value. This allows us to show the existence of a low distortion embedding as well as obtain a randomized algorithm to discover the embedding via random projections. The original proof of Johnson and Lindenstrauss [JL84] has been greatly simplified by the algorithmic proofs of Gupta-Dasgupta [GD02], Indyk-Motwani [IM98] and Arriaga-Vempala [VA06]. However, all these techniques involve sampling from continuous distributions which make them somewhat impractical for database purposes where one would like to perform operations via simple SQL queries. This problem was solved by a beautiful result due to Achlioptas [Ach01] who showed that one can in fact use a projection matrix with each entry chosen independently from the distribution $U\{-1, +1\}$. (In fact, as shown in [VA06], any distribution that is symmetric about the origin with the second moment as unity and bounded higher even moments can be used.) This is most suited to a database application where the random projection can be applied by simply splitting the attribute set into two halves by first sampling and summing up the attributes in each set, and then taking the difference of the two sums, and finally repeating this as many times as is the dimensionality of the projected space. We now state the main result of Achlioptas [Ach01] which assures that our algorithmic results are readily applicable to database situations as well.

Lemma 1 ([Ach01]). *Let $R = (r_{ij})$ be a random $d \times k$ matrix, such that each entry r_{ij} is chosen independently according to $U\{+1, -1\}$. For any fixed unit vector $u \in \mathbb{R}^d$, and any $\epsilon > 0$, let $u' = \sqrt{\frac{d}{k}}(R^T u)$. Then, $E[\|u'\|^2] = \|u\|^2$ and $\Pr[(1 - \epsilon)\|u\|^2 < \|u'\|^2 < (1 + \epsilon)\|u\|^2] \geq 1 - e^{-\frac{k}{2}\left(\frac{\epsilon^2}{2} - \frac{\epsilon^3}{3}\right)}$*

This establishes the Johnson-Lindenstrauss lemma. For a given value of ϵ , the dimensionality of the projected space (i.e. $O(\epsilon^{-2} \log n)$) is chosen in order to ensure an inverse polynomial error probability which facilitates the application of the union bound to ensure that none of the pairwise distances in the n -point set is distorted too much. The result also ensures that even the inner products are preserved to an arbitrarily low additive error; this is characterized by the following corollary.

Corollary 1 ([VA06]). *Let u, v be unit vectors in \mathbb{R}^d . Then, for any $\epsilon > 0$, a random projection of these vectors to yield the vectors u' and v' respectively satisfies $\Pr[u \cdot v - \epsilon \leq u' \cdot v' \leq u \cdot v + \epsilon] \geq 1 - 4e^{-\frac{k}{2}\left(\frac{\epsilon^2}{2} - \frac{\epsilon^3}{3}\right)}$*

Proof. Apply Lemma 1 to the vectors u, v and $u - v$. The result follows from using simple facts concerning inner products. \square

We shall be using the properties of the embedding described above to obtain low distortion embeddings for various statistical distance measures. To facilitate the discussion we refer to the process of mapping high-dimensional point sets to low-dimensional ones via random projections as *JL-type embeddings*. We now develop some of the terminology that will be used later. In

the discussion below, we assume that the histograms to be normalized, i.e., they correspond to probability distributions.

Definition 3 (Representative vector). *Given a d -dimensional histogram $P = (p_1, \dots, p_d)$, let \sqrt{P} denote the unit vector $(\sqrt{p_1}, \dots, \sqrt{p_d})$. We shall call this the representative vector of P .*

Definition 4 (α -constrained histogram). *A histogram $P = (p_1, p_2, \dots, p_d)$ is said to be α -constrained if $p_i \geq \frac{\alpha}{d}$ for $i = 1, 2, \dots, d$.*

This ensures that the α -constrained histograms have a level of “smoothness” to them and are not extremely skewed. The following result holds for all α -constrained histograms.

Observation 1. *Given two α -constrained histograms P and Q , the inner product between the representative vectors is at least α , i.e., $\langle \sqrt{P}, \sqrt{Q} \rangle \geq \alpha$.*

For convenience, we will denote $\frac{\alpha}{d}$ by β . A d -dimensional β -constrained distribution will then imply a distribution that is α -constrained with $\alpha = \beta \cdot d$. Since the histograms are normalized, α must be less than 1. In other words, $\beta \leq \frac{1}{d}$. We next examine three statistical distance measures starting with the Bhattacharyya class of distance measures.

3 The Bhattacharyya Class of Distance Measures

In the field of pattern classification, more specifically Bayesian decision theory, the Bhattacharyya bound is an upper-bound on the expected error rate of a Bayesian decision process [DHS00]. For a binary classification task on a feature x with the two categories as ω_1 and ω_2 and the likelihood parameters characterized by the distributions $p(x|\omega_i)$ for $i = 1, 2$, the Bhattacharyya bound on the error probability of a Bayesian classifier, ignoring the priors, is given by

$$\Pr\{\text{error}\} \leq \int \sqrt{p(x|\omega_1)p(x|\omega_2)} dx$$

This is known as the *Bhattacharyya coefficient* between the two distributions. For two histograms $P = (p_1, p_2, \dots, p_d)$ and $Q = (q_1, q_2, \dots, q_d)$ with $\sum_{i=1}^d p_i = \sum_{i=1}^d q_i = 1$ and each $p_i, q_i \geq 0$, the *Bhattacharyya coefficient* [Bha43] is described as

$$BC(P, Q) = \sum_{i=1}^d \sqrt{p_i q_i}$$

Using this coefficient, two distance measures can be defined as follows. The *Bhattacharyya distance* [Bha43] is defined as follows

$$BD(P, Q) = -\ln BC(P, Q)$$

It is easy to see that this measure does not form a metric. Another distance measure in this class, namely, the *Hellinger distance* [SWWJ08] between distributions is defined as

$$H(P, Q) = 1 - BC(P, Q) = \frac{1}{2} \left(\left\| \sqrt{P} - \sqrt{Q} \right\| \right)^2$$

The fact that $H(P, Q)$ is the Euclidean distance between the points \sqrt{P} and \sqrt{Q} allows us to state the following theorem.

Theorem 2. *The Hellinger distance admits a low distortion dimensionality reduction.*

Proof. Since the Hellinger distance between the two histograms is the Euclidean distance between their representative vectors, given a set of histograms, if we subject the corresponding set of representative vectors to a JL-type embedding then Lemma 1 ensures that the Euclidean distance between the embedded representative vectors is a $1 \pm \epsilon$ approximation of the Hellinger distance between the corresponding histograms with high probability. \square

3.1 Dimensionality Reduction for the Bhattacharyya Distance

We now consider the possibility of extending this idea to the Bhattacharyya distance as well which would provide us with dimensionality reduction for the Bhattacharyya distance. Given a set of histograms under the Bhattacharyya distance that are α -constrained and an error parameter ϵ , we perform a JL-type embedding with the error parameter appropriately set. This embedding constitutes a dimensionality reduction as we impose the Bhattacharyya distance on the new space. The following theorem shows that this embedding only incurs a small additive error.

Theorem 3. *A JL-type embedding of a set of α -constrained histograms under the Bhattacharyya distance measure with the error parameter set to $\epsilon' = \frac{\epsilon\alpha}{2}$ incurs only an additive error of ϵ , i.e., if P, Q are the initial histograms transformed respectively to P', Q' , then*

$$BD(P, Q) - \epsilon \leq BD(P', Q') \leq BD(P, Q) + \epsilon$$

Proof. By Corollary 1, we have the following with high probability:

$$\langle \sqrt{P}, \sqrt{Q} \rangle - \epsilon' \leq \langle \sqrt{P'}, \sqrt{Q'} \rangle \leq \langle \sqrt{P}, \sqrt{Q} \rangle + \epsilon'$$

Taking $-\ln(\cdot)$ throughout and using the definition of the Bhattacharyya distance, we have

$$\begin{aligned} BD(P', Q') &\geq BD(P, Q) - \ln \left(1 + \frac{\epsilon'}{\langle \sqrt{P}, \sqrt{Q} \rangle} \right) \\ BD(P', Q') &\leq BD(P, Q) + \ln \left(\frac{1}{1 - \frac{\epsilon'}{\langle \sqrt{P}, \sqrt{Q} \rangle}} \right) \end{aligned}$$

Since the distributions are α -constrained, we have $\langle \sqrt{P}, \sqrt{Q} \rangle \geq \alpha$. Hence,

$$\begin{aligned} BD(P', Q') &\geq BD(P, Q) - \ln \left(1 + \frac{\epsilon'}{\alpha} \right) \\ BD(P', Q') &\leq BD(P, Q) + \ln \left(\frac{1}{1 - \frac{\epsilon'}{\alpha}} \right) \end{aligned}$$

For any x , $e^x \geq 1 + x$. Hence,

$$\ln \left(1 + \frac{\epsilon'}{\alpha} \right) \leq \frac{\epsilon'}{\alpha}$$

Also, the function $f(x) = 2x - \ln\left(\frac{1}{1-x}\right)$ is positive for all $x \leq \frac{1}{2}$. Hence, for $\frac{\epsilon'}{\alpha} \leq \frac{1}{2}$ (which is true since $\epsilon' = \frac{\epsilon \cdot \alpha}{2}$ and $\epsilon \leq 1$), we have

$$\ln\left(\frac{1}{1 - \frac{\epsilon'}{\alpha}}\right) \leq \frac{2\epsilon'}{\alpha}$$

This implies the following bounds on $BD(P, Q)$

$$BD(P, Q) - \frac{\epsilon'}{\alpha} \leq BD(P', Q') \leq BD(P, Q) + \frac{2\epsilon'}{\alpha}$$

which gives us the desired result since $\epsilon' = \frac{\epsilon \cdot \alpha}{2}$. \square

The natural question that arises now is whether the Bhattacharyya distance, being a non-metric, also admits low distortion embeddings into metric spaces. Next, we develop a proof technique that shows that the distortion incurred by any embedding of point sets under the Bhattacharyya distance into a metric space can be made arbitrarily large by including appropriately chosen histograms.

3.2 The Relaxed Triangle Inequality Technique

In order to present the proof, we first define λ -relaxed triangle inequality for a distance measure. This essentially parallels the definition of a *relaxed metric* as defined in [CM08].

Definition 5 (λ -Relaxed Triangle Inequality). *A set X equipped with a distance function $d : X \times X \rightarrow \mathbb{R}^+ \cup \{0\}$, is said to satisfy the λ -relaxed triangle inequality if there exists some constant $\lambda \leq 1$ such that for all triplets $p, q, r \in X$, the following holds*

$$d(p, r) + d(r, q) \geq \lambda \cdot d(p, q)$$

Metrics satisfy the λ -relaxed triangle inequality for $\lambda = 1$. The following result allows us to arrive at lower bounds on the distortion of embeddings into metric spaces for a distance measure that violates a relaxed triangle inequality.

Lemma 2. *Any embedding of a set X equipped with a distance function d that does not satisfy the λ -relaxed triangle inequality into a metric space incurs a distortion of at least $\frac{1}{\lambda}$.*

Proof. Since (X, d) does not satisfy the λ -relaxed triangle inequality, there exist points $p, q, s \in X$ such that $d(p, s) + d(s, q) < \lambda \cdot d(p, q)$. Now, let (X, d) be embedded into a metric space (Y, ρ) via the mapping f that incurs a distortion D . This implies that, for all points $x, y \in X$, we have

$$r \cdot d(x, y) \leq \rho(f(x), f(y)) \leq D \cdot r \cdot d(x, y)$$

Next, consider the three points $p, q, s \in X$. Since (Y, ρ) is a metric space, it satisfies the triangle inequality for the embeddings of these points. Hence

$$\begin{aligned} \rho(f(p), f(s)) + \rho(f(s), f(q)) &\geq \rho(f(p), f(q)) \\ rD \cdot d(p, s) + rD \cdot d(s, q) &> r \cdot d(p, q) \\ rD\lambda \cdot d(p, q) &> r \cdot d(p, q) \end{aligned}$$

Hence we have $D > \frac{1}{\lambda}$. \square

In general, if (Y, ρ) , i.e. the space being embedded into, satisfies a λ' -relaxed triangle inequality, then we get a lower bound of $\frac{\lambda'}{\lambda}$ on the value of distortion of (X, d) into (Y, ρ) .

3.3 Lower Bound on Distortion for Embeddings into Metric Spaces

We now appeal to the relaxed triangle inequality argument by constructing point sets under the Bhattacharyya distance that fail to satisfy the relaxed triangle inequality and then applying Lemma 2 to get a lower bound on the distortion.

The idea is to choose three distributions P, Q, R such that the angle between the representative vectors of P and R is almost $\pi/2$ (i.e., the similarity is almost 0) while the angle between the representative vectors of P and Q and those of Q and R is much less than $\pi/2$. This ensures that $BD(P, R)$ is much larger than $BD(P, Q)$ and $BD(Q, R)$. Our result is characterized by the following theorem.

Theorem 4. *There exist d -dimensional β -constrained distributions such that any embedding of these distributions under the Bhattacharyya distance measure into a metric space must incur a distortion of*

$$D = \begin{cases} \Omega\left(\frac{\ln \frac{1}{d\beta}}{\ln d}\right) & \text{when } \beta > \frac{4}{d^2} \\ \Omega\left(\frac{\ln \frac{1}{\beta}}{\ln d}\right) & \text{when } \beta \leq \frac{4}{d^2} \end{cases}$$

Proof. We know that the Bhattacharyya coefficient for two distributions is the inner product between their corresponding vector representations on the unit sphere. Recalling the definitions,

$$\begin{aligned} BC(p, q) &= \sum_{i=1}^d (\sqrt{p_i} \cdot \sqrt{q_i}) \\ BD(p, q) &= -\ln BC(p, q) \end{aligned}$$

Consider the following β -constrained distributions which satisfy the above properties :

$$\begin{aligned} P &= (1 - (d-1)\beta, \beta, \dots, \beta) \\ Q &= \left(\frac{1}{d}, \frac{1}{d}, \dots, \frac{1}{d}\right) \\ R &= (\beta, 1 - (d-1)\beta, \dots, \beta) \end{aligned}$$

Now we have

$$\begin{aligned} \frac{BD(P, Q) + BD(Q, R)}{BD(P, R)} &= \frac{\ln\left(\langle \sqrt{P}, \sqrt{Q} \rangle \cdot \langle \sqrt{Q}, \sqrt{R} \rangle\right)}{\ln\left(\langle \sqrt{P}, \sqrt{R} \rangle\right)} \\ \langle \sqrt{P}, \sqrt{R} \rangle &= (d-2)\beta + 2\sqrt{\beta - (d-1)\beta^2} \\ \langle \sqrt{P}, \sqrt{Q} \rangle &= \frac{\sqrt{1 - (d-1)\beta} + \sqrt{\beta}(d-1)}{\sqrt{d}} \\ &= \langle \sqrt{Q}, \sqrt{R} \rangle \end{aligned}$$

Applying Lemma 2 we get the following bound on the distortion

$$D > \frac{\ln\left(\frac{1}{(d-2)\beta + 2\sqrt{\beta - (d-1)\beta^2}}\right)}{\ln\left(\frac{\sqrt{d}}{\sqrt{1 - (d-1)\beta} + \sqrt{\beta}(d-1)}\right)}$$

Since $\beta > 0$ and $1 - (d-1)\beta > \frac{1}{d}$, we have $\sqrt{1 - (d-1)\beta} + \sqrt{\beta}(d-1) > \frac{1}{d}$. In order to get a lower bound on the numerator, we need an upper bound on $(d-2)\beta + 2\sqrt{\beta}\sqrt{1 - (d-1)\beta}$. Using the fact that $1 - (d-1)\beta \leq 1$, we get an upper bound of $d\beta + 2\sqrt{\beta}$ on the above expression. In case $\beta > \frac{4}{d^2}$

$$D = \Omega\left(\frac{\ln \frac{1}{d\beta}}{\ln d}\right)$$

Otherwise, $d\beta + \sqrt{\beta} < 3\sqrt{\beta}$, which implies that

$$D = \Omega\left(\frac{\ln \frac{1}{\beta}}{\ln d}\right)$$

□

In the following section, we demonstrate that this bound is tight up to a $O(d \ln d)$ factor.

3.4 A Metric Embedding for the Bhattacharyya distance

In this section, we first show that the Bhattacharyya distance is very closely related to the Hellinger distance measure as previously defined. Since the Hellinger distance forms a metric in the positive orthant, this allows us to get an upper bound on the distortion which, for a fixed dimension, almost matches the lower bound.

Theorem 5. *For any two d -dimensional β -constrained distributions P and Q with $\beta < \frac{1}{2d}$, we have*

$$H(P, Q) \leq BD(P, Q) \leq \frac{d}{1 - 2\beta d} \ln \frac{1}{(d-1)\beta} H(P, Q)$$

Proof. For two distributions P, Q , recall

$$\begin{aligned} BC(P, Q) &= 1 - H(P, Q) \\ BD(P, Q) &= -\ln\left(\sum_{i=1}^d \sqrt{p_i} \sqrt{q_i}\right) \\ &= -\ln(1 - H(P, Q)) \\ &= \sum_{k=1}^{\infty} \frac{H(P, Q)^k}{k} \end{aligned}$$

To arrive at the lower bound we truncate the infinite series at the first term. For the upper bound, we need to use the fact that the function $f(x) = -\ln(1-x)$ is convex. The maximum Hellinger distance between any two β -constrained distributions is $2(\sqrt{1 - (d-1)\beta} - \beta)^2$. Let, $a = (\sqrt{1 - (d-1)\beta} - \beta)^2$. Due to convexity of f , the line mx lies above the curve $-\ln(1-x)$ where $m = \frac{f(a)}{a}$. Therefore, we have

$$BD(P, Q) = -\ln(1 - H(P, Q)) \leq \frac{1}{a} \ln\left(\frac{1}{1-a}\right) H(P, Q)$$

Also, $1 - a = (d - 1)\beta + 2\beta\sqrt{1 - (d - 1)\beta} - \beta^2 \geq (d - 1)\beta$ since $2\sqrt{1 - (d - 1)\beta} - \beta \geq 0$. Thus we get

$$BD(P, Q) \leq \frac{d}{1 - 2\beta d} \ln \left(\frac{1}{(d - 1)\beta} \right) H(P, Q)$$

This implies that the identity embedding of a point set under the Bhattacharyya distance into one under the Hellinger distance incurs a distortion of $\frac{d}{1 - 2\beta d} \ln \frac{1}{(d - 1)\beta}$. \square

For constant d and sufficiently small β , the lower bound presented in Section 3.3 is essentially $\Omega \left(\ln \frac{1}{\beta} \right)$, whereas the embedding presented in this section has a distortion of $O \left(\ln \frac{1}{\beta} \right)$ which implies that the lower bound is tight. In general it can be seen using Theorems 4 and 5 that for sufficiently small β the lower bound presented is tight up to a factor of $O(d \ln d)$. Further, the result presented in Theorem 2 can be used to perform dimensionality reduction as well.

4 The Kullback-Leibler Divergence

The Kullback-Leibler divergence arises in information theoretic settings where probability distributions are evaluated in terms of their entropy or the amount of information they contain. The Kullback-Leibler divergence measures the difference between the relative entropy and the self entropy of two distributions. Given two histograms $P = \{p_1, p_2, \dots, p_d\}$ and $Q = \{q_1, q_2, \dots, q_d\}$, the Kullback-Leibler divergence between the two distributions is defined as

$$KL(P, Q) = \sum_{i=1}^d p_i \ln \frac{p_i}{q_i}$$

Informally, it gives an asymptotic lower bound on the overhead incurred in terms of encoding length if one were to encode data assuming it to be generated by a random source characterized by Q when in fact the source is characterized by P . The Kullback-Leibler divergence is non-symmetric and unbounded, i.e., for any given $c > 0$, one can construct histograms whose Kullback-Leibler divergence exceeds c . In order to avoid these singularities, we assume that the histograms are β -constrained.

Lemma 3. *Given two β -constrained histograms P, Q , $0 \leq KL(P, Q) \leq \ln \frac{1}{\beta}$.*

Proof. The lower bound follows directly from Jensen inequality [DHS00]. For the upper bound, since we know that $\frac{p_i}{q_i} \leq \frac{1}{\beta}$ for all $i = 1, 2, \dots, d$, we can write

$$KL(P, Q) = \sum_{i=1}^d p_i \ln \frac{p_i}{q_i} \leq \sum_{i=1}^d p_i \ln \frac{1}{\beta} = \ln \frac{1}{\beta}$$

For $\beta = O \left(\frac{1}{d} \right)$, the upper bound is tight up to a constant factor. \square

In the following discussion, we show that low distortion embeddings into metric spaces cannot exist for the Kullback-Leibler divergence. In order to show this, we utilize the relaxed triangle inequality presented in Section 3.2 and explicitly construct point sets that violate the relaxed triangle inequality. We also develop another technique that exploits the fact that the Kullback-Leibler divergence is not symmetric. We first present this new proof technique before moving on to prove bounds utilizing both the proof techniques.

4.1 The Asymmetry Technique

We present a general result that can be used to prove lower bounds on the embedding distortion when we intend to embed a non-symmetric distance measure into a metric space. The idea is to exploit the existence of two points p, q for which there is a large gap between the distances between p to q and q to p . This idea is formalized in Lemma 4 using the following definition.

Definition 6 (γ -Relaxed Symmetry). *A set X equipped with a distance function $d : X \times X \rightarrow \mathbb{R}^+ \cup \{0\}$, is said to satisfy γ -relaxed symmetry if there exists $\gamma \geq 0$ such that for all point pairs $p, q \in X$, the following holds*

$$|d(p, q) - d(q, p)| \leq \gamma$$

Note that metrics satisfy the γ -relaxed symmetry for $\gamma = 0$.

Lemma 4. *Given a set X equipped with a distance function d that does not satisfy the γ -relaxed symmetry such that $d(x, y) \leq M$ for all $x, y \in X$, any embedding of X into a metric space incurs a distortion of at least $1 + \frac{\gamma}{M}$.*

Proof. Since (X, d) does not satisfy the γ -relaxed symmetry, there exist points $p, q \in X$ such that $|d(p, q) - d(q, p)| > \gamma$. If (X, d) is embeddable via a mapping f into a metric space (Y, ρ) with a distortion of D then for some constant $r > 0$,

$$r \cdot d(x, y) \leq \rho(f(x), f(y)) \leq D \cdot r \cdot d(x, y)$$

Without loss of generality, assume that $d(p, q) > d(q, p)$. Since (Y, ρ) is a metric space, it is symmetric, which implies that $\rho(f(p), f(q)) = \rho(f(q), f(p))$. Since $d(p, q) > d(q, p) + \gamma$, we have

$$\begin{aligned} \rho(f(p), f(q)) - r \cdot d(q, p) &> r \cdot \gamma \\ \frac{\rho(f(p), f(p))}{r \cdot d(q, p)} - 1 &> \frac{r \cdot \gamma}{r \cdot d(p, q)} \\ D \geq \frac{\rho(f(p), f(p))}{r \cdot d(q, p)} &> 1 + \frac{\gamma}{M} \end{aligned}$$

This implies that the distortion is at least $1 + \frac{\gamma}{M}$. □

4.2 Lower Bounds on Distortion for Embeddings into Metric Spaces

We now apply the above lemma to show that one cannot hope to obtain an almost isometric embedding of the Kullback-Leibler divergence into any metric space. We show the existence of two histograms P and Q such that $|KL(P, Q) - KL(Q, P)|$ is large. The result is formally stated in the following theorem.

Theorem 6. *For sufficiently large d and small β , there exists a set S of d -dimensional β -constrained histograms and a constant $c > 0$ such that any embedding of S into a metric space incurs a distortion of at least $1 + c$.*

Proof. The idea is to choose two distributions which violate a δ -relaxed symmetry for large δ . Consider the following two distributions where $\beta \neq \frac{1}{d}$

$$\begin{aligned} P &= \left\{ \frac{1}{d}, \frac{1}{d}, \dots, \frac{1}{d} \right\} \\ Q &= \{1 - (d-1)\beta, \beta, \dots, \beta\} \end{aligned}$$

Define $\Delta KL(P, Q) = |KL(P, Q) - KL(Q, P)|$. Since we have

$$\begin{aligned} KL(P, Q) &= \left(1 - \frac{1}{d}\right) \ln \frac{1}{\beta d} - \frac{1}{d} \ln(d(1 - (d-1)\beta)) \\ KL(Q, P) &= \beta(d-1) \ln \beta d + (1 - (d-1)\beta) \ln(d(1 - (d-1)\beta)) \end{aligned}$$

by rearranging the terms we get

$$\Delta KL(P, Q) = \left| \left(1 - \frac{1}{d} + \beta(d-1)\right) \ln \frac{1}{\beta d} - \left(\frac{1}{d} + 1 - (d-1)\beta\right) \ln(d(1 - (d-1)\beta)) \right|$$

For sufficiently large d , we consider the situation when β is large i.e. say $\beta = \frac{1}{\Theta(d)}$. In this case we have $\Delta KL(P, Q) = \left| \Theta\left(\ln \frac{1}{d\beta}\right) - \Theta(\ln d) \right| = \Theta(\ln d)$. Since for β -constrained distributions, the maximum inter point distance i.e. $M = \ln \frac{1}{\beta}$, we get the a lower bound on the distortion by using Lemma 4 as $1 + \frac{\Theta(\ln d)}{\ln \frac{1}{\beta}}$ which is $1 + \Theta(1)$ as $\beta = \frac{1}{\Theta(d)}$.

For small β - say $\beta = o\left(\frac{1}{d^4}\right)$, since $d > 2$ we get

$$\Delta KL(P, Q) \geq \frac{1}{2} \ln \frac{1}{\beta d} - \frac{3}{2} \ln d = \frac{1}{2} \ln \frac{1}{\beta d^4}$$

Using a similar argument as above, we get a lower bound on the distortion as

$$D = 1 + \Omega\left(\frac{\ln \frac{1}{\beta d^4}}{\ln \frac{1}{\beta}}\right) = 1 + \Omega(1)$$

Hence we conclude that any embedding of point sets which contain the points P and Q into a metric space must have a distortion D of at least $1 + c$ for some constant c . \square

The above argument shows the impossibility of obtaining almost isometric (i.e., with distortion arbitrarily closed to 1) embeddings of β -constrained histograms under the Kullback-Leibler divergence. Since $\Delta(P, Q)$ can be at most $\ln \frac{1}{\beta}$, for any two β -constrained distributions, using this technique, a different choice of points can at best provide a constant factor improvement over the above bounds. It should be noted that one cannot hope to get significant improvement on the above bounds via this technique by choosing two different points in the probability simplex. However, an application of the relaxed triangle inequality technique shows that the situation is much worse. We will now demonstrate that the Kullback-Leibler divergence admits point sets which violate the λ -relaxed triangle inequality, where λ can be made arbitrarily small. This implies (by applying Lemma 2) that the distortion into any metric space can be made arbitrarily large.

Theorem 7. *For sufficiently large d , there exist d -dimensional β -constrained distributions such that embedding these under the Kullback-Leibler divergence into a metric space must incur a distortion of $\Omega\left(\frac{\ln \frac{1}{d\beta}}{\ln\left(d \ln \frac{1}{\beta}\right)}\right)$.*

Proof. We construct three β -constrained distributions that fail to satisfy a relaxed triangle inequality under the Kullback-Leibler divergence. Consider the following distributions. The parameters ϵ

and c will be fixed later. Let

$$\begin{aligned} P &= \left(\frac{1}{d}, \frac{1}{d}, \dots, \frac{1}{d} \right) \\ Q &= (1 - (d-1)\epsilon, \epsilon, \dots, \epsilon) \\ R &= (1 - (d-1)e^{-c}, e^{-c}, \dots, e^{-c}) \end{aligned}$$

where $\frac{1}{d} \geq \epsilon > e^{-c} \geq \beta$. We have

$$\begin{aligned} KL(P, Q) &= \left(1 - \frac{1}{d}\right) \ln \frac{1}{d\epsilon} + \frac{1}{d} \ln \frac{1}{d(1 - (d-1)\epsilon)} \\ &\leq \ln \frac{1}{d\epsilon} \\ KL(Q, R) &= (1 - (d-1)\epsilon) \ln \frac{1 - (d-1)\epsilon}{1 - (d-1)e^{-c}} + (d-1)\epsilon \ln(\epsilon e^c) \\ &\leq (d-1)\epsilon \ln \epsilon + (d-1)c\epsilon \\ KL(P, R) &= \left(1 - \frac{1}{d}\right) \ln \frac{1}{de^{-c}} + \frac{1}{d} \ln \frac{1}{d(1 - (d-1)e^{-c})} \\ &\geq \frac{1}{2}(c - \ln d) + \frac{1}{d} \ln \frac{1}{d} \\ &= \Omega(c - \ln d) - O(1) \end{aligned}$$

Using the above inequalities,

$$\begin{aligned} \lambda &= \frac{KL(P, Q) + KL(Q, R)}{KL(P, R)} \\ &= O\left(\frac{\ln \frac{1}{d\epsilon} + (d-1)\epsilon \ln \epsilon + (d-1)c\epsilon}{c - \ln d}\right) \end{aligned}$$

Hence, any point set containing these three points violates the λ -relaxed triangle inequality. Now, using Lemma 2, the distortion for the Kullback-Leibler divergence is

$$D > \frac{1}{\lambda} = \Omega\left(\frac{c - \ln d}{\ln \frac{1}{d\epsilon} + d\epsilon \ln \epsilon + dc\epsilon}\right)$$

Since $\epsilon \ln \epsilon < 0$, hence

$$D = \Omega\left(\frac{c - \ln d}{\ln \frac{1}{d\epsilon} + dc\epsilon}\right)$$

Consider the function $f(c, \epsilon) = \frac{c - \ln d}{\ln \frac{1}{d\epsilon} + dc\epsilon}$. It turns out that $\frac{\partial f}{\partial c} > 0$ for all values of c . Hence, the maxima is achieved at the maximum value of c which is $\ln \frac{1}{\beta}$. Furthermore we find that $\frac{\partial f}{\partial \epsilon} = 0$ at $\epsilon = \frac{1}{dc} = \frac{1}{d \ln \frac{1}{\beta}}$. It can be confirmed that this extrema is actually a maxima. For a fixed value of d we can choose β small enough to make sure that the value of ϵ is at least β . For these values of c and ϵ we get the lower bound as

$$D = \Omega\left(\frac{\ln \frac{1}{d\beta}}{\ln\left(d \ln \frac{1}{\beta}\right) + 1}\right)$$

Thus, the result follows. \square

Interpreting the Lower Bounds: The above bounds show how the Kullback-Leibler divergence behaves near the uniform distribution and near the boundaries of the probability simplex. The bounds indicate that near the uniform distribution, asymmetry makes the Kullback-Leibler divergence hard to approximate by a metric but as we move away from the uniform distribution the hardness is because of the violation of the relaxed triangle inequality. More formally, it can be seen that for point sets which are β -constrained for large β (say $\beta = \Omega\left(\frac{1}{d}\right)$), the lower bound using the asymmetry argument gives a $1 + \Theta(1)$ bound whereas the triangle inequality argument gives a $o(1)$ bound. For smaller β (say $\beta = o\left(\frac{1}{d^4}\right)$) we get a better lower bound using the relaxed triangle inequality argument. This lower bound behaves asymptotically as $\frac{\ln \frac{1}{\beta}}{\ln \ln \frac{1}{\beta}}$ which can be made arbitrarily large. Note that the asymmetry argument gives a constant lower bound even for very small β but this only shows the ineffectiveness of this proof technique for small β .

4.3 An Embedding for the Kullback-Leibler divergence

In this section, we examine the properties of the identity embedding of point sets under the Kullback-Leibler divergence into the l_2^2 distance measure. Once we have obtained this result one can again apply JL-type embeddings to achieve dimensionality reduction as well. To obtain this bound we use a well known inequality in information theory due to Pinsker [Top00]. Our result is characterized by the following theorem.

Theorem 8. *For any two d -dimensional β -constrained distributions P and Q ,*

$$\frac{l_2^2(P, Q)}{2} \leq KL(P, Q) \leq \left(\frac{1}{2\beta} + \frac{1}{3\beta^5} \right) l_2^2(P, Q)$$

Proof. The lower bound essentially follows from Pinsker's inequality [Top00] which states that

$$\frac{l_1^2(P, Q)}{2} \leq KL(P, Q)$$

Since $l_1(P, Q) \geq l_2(P, Q)$, the lower bound follows automatically. For the upper bound, we use Taylor's Theorem on the expression for $KL(P, Q)$

$$\begin{aligned} KL(P, Q) &= \sum_{i=1}^n p_i \ln \frac{p_i}{q_i} \\ &= \sum_{i=1}^d -p_i \ln \left(1 - \frac{p_i - q_i}{p_i} \right) \end{aligned}$$

By Taylor's Theorem, there exists ϵ such that $|\epsilon| \leq \left| \frac{p_i - q_i}{p_i} \right|$, for which the following holds :

$$\begin{aligned} KL(P, Q) &= \sum_{i=1}^d p_i \left(\frac{p_i - q_i}{p_i} + \frac{(p_i - q_i)^2}{2p_i^2} + \frac{1}{(1 - \epsilon)^3} \cdot \frac{(p_i - q_i)^3}{3p_i^3} \right) \\ &= \sum_{i=1}^d \left(\frac{(p_i - q_i)^2}{2p_i} + \frac{1}{(1 - \epsilon)^3} \cdot \frac{(p_i - q_i)^3}{3p_i^2} \right) \end{aligned}$$

Since $|\epsilon| \leq \left| \frac{p_i - q_i}{p_i} \right|$, $\frac{1}{(1-\epsilon)^3} \leq \frac{1}{\beta^3}$, and $\left| \frac{p_i - q_i}{p_i} \right| \leq \frac{1}{\beta}$, we have $\frac{1}{(1-\epsilon)^3} \cdot \frac{(p_i - q_i)^2}{3p_i} \cdot \frac{(p_i - q_i)}{p_i} \leq \frac{(p_i - q_i)^2}{3\beta^5}$. Therefore,

$$KL(P, Q) \leq \left(\frac{1}{2\beta} + \frac{1}{3\beta^5} \right) l_2^2(P, Q)$$

The distortion of this identity embedding is $O\left(\frac{1}{\beta^5}\right)$. \square

Although this embedding does not give us a provably small distortion, it can still be used in practical situations since the embedding is into l_2^2 space and it allows for low distortion dimensionality reduction using the Johnson-Lindenstrauss Lemma.

5 The Class of Quadratic Form Distance Measures

Consider the vector space \mathbb{R}^d . Given a $d \times d$ positive definite matrix A , the *Quadratic Form Distance measures (QFDs)* define a distance measure over \mathbb{R}^d . If $x, y \in \mathbb{R}^d$, then $Q_A(x, y)$ is defined to be

$$Q_A(x, y) = \sqrt{(x - y)^T A (x - y)}$$

These distance measures can be seen as acting on a distorted Euclidean space. When A is a diagonal matrix with positive entries, the corresponding QFDs are weighted Euclidean distance measures. The family of quadratic form distances are actually defined for general positive semi-definite matrices. However, for positive definite matrices, the distance measure Q_A forms a metric. We now show that every QFD can be embedded into a low-dimensional space with low distortion in the inter-point distances.

Theorem 9. *The family of quadratic form distance measures admit a low distortion JL-type embedding.*

Proof. Every quadratic form distance measure forming a metric is characterized by a square matrix A which is positive definite. However, every positive definite matrix A can be subjected to a Cholesky Decomposition of the form $A = L^T L$ [GL96]. Consider the transformation $x \mapsto R(Lx)$ where R is the random projection matrix involved in the Johnson-Lindenstrauss Lemma. Consider two points $x, y \in \mathbb{R}^d$, then

$$Q_A(x, y) = \sqrt{(x - y)^T A (x - y)} = \sqrt{(L(x - y))^T (L(x - y))}$$

which is the Euclidean distance between the points Lx and Ly . Thus, the proposed transformation gives us a low distortion embedding since the problem has been reduced to that in the undistorted Euclidean space where the Johnson-Lindenstrauss Lemma is applicable. \square

The previous theorem can be easily seen to provide a simple algorithm to reduce the dimensionality of the data points and still preserve the distance as given by the QFD. Given this formulation we now look at the Mahalanobis distance which is a special case of the QFD measure where the positive definite matrix is taken to be the covariance matrix of a normal multivariate probability distribution. Given the construction of low distortion embeddings for QFDs, the following result is immediate.

Corollary 2. *The Mahalanobis metric admits a randomized polynomial time low distortion JL-type embedding.*

6 Conclusions

We have investigated various statistical distance measures from the point of view of dimensionality reduction and embeddability into metric spaces. We examined and presented novel dimensionality reduction techniques for the Bhattacharyya distance, the Hellinger distance and the Mahalanobis distance measure using the Johnson-Lindenstrauss Lemma.

We also examined the question of finding low distortion embeddings of the Bhattacharyya distance and the Kullback-Leibler divergence which are non-metric distance measures into metric spaces. We developed two novel techniques that can be used to prove lower bounds on the distortion that must be incurred by any such embedding.

For the Bhattacharyya distance, we demonstrated that the lower bound presented is almost tight by analyzing its relationship between the Hellinger distance which forms a metric. We performed a similar exercise for the Kullback-Leibler divergence to relate it with the l_2^2 measure. Although it does not match the lower bounds, it is of practical significance since it allows for dimensionality reduction.

The question that we leave open is that of dimensionality reduction under the Kullback-Leibler divergence. Our preliminary investigations show that this is unlikely if one wants the resulting embedded objects to lie on the low-dimensional probability simplex. Also, it remains to be seen if the methods developed in this paper, viz., the adaptations of random projections to various distance measures and the proof techniques developed, find applications for other widely used statistical distance measures, many of which are non-metrics.

References

- [Ach01] Dimitris Achlioptas. Database-friendly Random Projections. In *ACM Symposium on Principles of Database Systems*, 2001.
- [Bha43] A. Bhattacharyya. On a Measure of Divergence between Two Statistical Populations Defined by their Probability Distributions. *Bulletin of Calcutta Mathematical Society*, 35:99–110, 1943.
- [Cay08] Lawrence Cayton. Fast Nearest Neighbor Retrieval for Bregman Divergences. In *International Conference on Machine Learning*, 2008.
- [CL08] Lei Chen and Xiang Lian. Efficient Similarity Search in Nonmetric Spaces with Local Constant Embedding. *IEEE Transactions on Knowledge and Data Engineering*, 20(3):321–336, 2008.
- [CM08] Kamalika Chaudhuri and Andrew McGregor. Finding Metric Structure in Information-Theoretic Clustering. In *Proceedings of COLT 2008*, pages 391–402, 2008.
- [CRM00] D. Comaniciu, V. Ramesh, and P. Meer. Real-Time Tracking of Non-Rigid Objects using Mean Shift. In *IEEE Conference on Computer Vision and Pattern Recognition*, volume 2, pages 142–149, 2000.
- [DHS00] Richard O. Duda, Peter E. Hart, and David G. Stork. *Pattern Classification*. Wiley Publications, 2nd edition, 2000.

- [FHVW03] Andy Fraser, Nick Hengartner, Kevin Vixie, and Brendt Wohlberg. Incorporating invariants in Mahalanobis distance based classifiers: Application to Face Recognition. In *International Joint Conference on Neural Networks*, 2003.
- [GD02] A. Gupta and Sanjoy Dasgupta. An elementary proof of the Johnson-Lindenstrauss Lemma. *Random Structures and Algorithms*, 22(1):60–65, 2002.
- [GIM07] Sudipto Guha, Piotr Indyk, and Andrew McGregor. Sketching Information Divergences. In *Proceedings of COLT 2007*, pages 424–438, 2007.
- [GL96] Gene H. Golub and Charles F. Van Loan. *Matrix computations*. Johns Hopkins University Press, 3rd edition, 1996.
- [IM98] Piotr Indyk and Rajeev Motwani. Approximate Nearest Neighbors: Towards Removing the Curse of Dimensionality. In *30th Symposium on Theory of Computing*, 1998.
- [IT03] Piotr Indyk and Nitin Thaper. Fast Image Retrieval via embeddings. In *3rd International Workshop on Statistical and Computational Theories of Vision*, 2003.
- [JL84] W. B. Johnson and J. Lindenstrauss. Extensions of Lipschitz maps into a Hilbert Space. *Contemporary Mathematics*, 26:189–206, 1984.
- [Kul59] S. Kullback. *Information Theory and Statistics*. John Wiley and Sons, 1959.
- [LBS06] V. Ljosa, A. Bhattacharya, and A. K. Singh. Indexing Spatially Sensitive Distance Measures Using Multi-Resolution Lower Bounds. In *International Conference on Extending Database Technology (EDBT)*, pages 865–883, 2006.
- [LS99] Chang-Hwan Lee and Dong-Guk Shin. Using Hellinger Distance in a nearest neighbour classifier for relational databases. *Knowledge-Based Systems*, 12:363–370, 1999.
- [LS03] Ce Liu and Hueng-Yeung Shum. Kullback-Leibler Boosting. In *IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, 2003.
- [Mah36] P. C. Mahalanobis. On the Generalised Distance in Statistics. *Proc. of the National Institute of Science of India*, 2:49–55, 1936.
- [Mat02] Jiří Matoušek. *Graduate Texts in Mathematics*, volume 212, chapter Lectures on Discrete Geometry. Springer, 2002.
- [MSB02] John Reidar Mathiassen, Amund Skavhaug, and Ketil Bø. Texture Similarity Measure Using Kullback-Leibler Divergence between Gamma Distributions. In *Proceedings of the 7th European Conference on Computer Vision-Part III*, pages 133–147, 2002.
- [NBN07] Frank Nielsen, Jean-Daniel Boissonnat, and Richard Nock. On Bregman Voronoi diagrams. In *SODA '07: Proceedings of the eighteenth annual ACM-SIAM symposium on Discrete algorithms*, pages 746–755, 2007.
- [RBD05] Md. Mahmudur Rahman, Prabir Bhattacharya, and Bipin C. Desai. Similarity searching in image retrieval with statistical distance measures and supervised learning. In *Pattern Recognition and Data Mining*, pages 315–324, 2005.

- [RTG00] Yossi Rubner, Carlo Tomasi, and Leonidas J. Guibas. The Earth Mover’s Distance as a Metric for Image Retrieval. *International Journal of Computer Vision*, 40(2):99–121, 2000.
- [Sam05] Hanan Samet. *Foundations of Multidimensional and Metric Data Structures*. Morgan Kaufmann Publishers, 2005.
- [SWWJ08] Hemant Sengar, Haining Wang, Duminda Wijesekera, and Sushil Jajodia. Detecting VoIP Floods using the Hellinger Distance. *IEEE Transactions on Parallel and Distributed Systems*, 19(6):794–805, 2008.
- [Top00] F. Topsøe. Some inequalities for information divergence and related measures of discrimination. *IEEE Transactions on Information Theory*, 46(9):1602–1609, 2000.
- [VA06] Santosh Vempala and Rosa Arriaga. Towards an Algorithmic Theory of Learning. *Machine Learning*, 63(2):161–182, 2006.
- [WBD97] Tzee-Jian Wu, John P. Burke, and Daniel B. Davison. A Measure of DNA Sequence Dissimilarity based on Mahalanobis Distance between Frequencies of Words. *Biometrics*, 53(4):1431–1439, 1997.