7 Distances

We have mainly been focusing on similarities so far, since it is easiest to explain locality sensitive hashing that way, and in particular the Jaccard similarity is easy to define in regards to the k-shingles of text documents. In this lecture we will define a *metric* and then enumerate several important distances and their properties.

In general, choosing which distance to use is an important, but often ignored modeling problem. The L_2 distance is often a default. This is likely because in many situations (but not all) it is very easy to use, and has some nice properties. Yet in many situations the L_1 distance is more robust and makes more sense.

7.1 Metrics

So what makes a good distance? There are two aspects to the answer to this question. The first is that it captures the "right" properties of the data, but this is a sometimes ambiguous modeling problem. The second is more well-defined; it is the properties which makes a distance a metric.

A distance $\mathbf{d} : \mathcal{X} \times \mathcal{X} \to \mathbb{R}^+$ is a bivariate operator (it takes in two arguments, say $a \in \mathcal{X}$ and $b \in \mathcal{X}$) that maps to $\mathbb{R}^+ = [0, \infty)$. It is a *metric* if

(M1) $\mathbf{d}(a, b) \geq 0$ (**non-negativity**)

(M2) $\mathbf{d}(a, b) = 0$ if and only if $a = b$ (**identity**)

(M3) $\mathbf{d}(a, b) = \mathbf{d}(b, a)$ (**symmetry**)

(M4) $\mathbf{d}(a, b) \leq \mathbf{d}(a, c) + \mathbf{d}(c, b)$ (**triangle inequality**)

A distance that satisfies (M1), (M3), and (M4) (but not necessarily (M2)) is called a *pseudometric*.

A distance that satisfies (M1), (M2), and (M4) (but not necessarily (M3)) is called a *quasimetric*.

7.2 Distances

We now enumerate a series of common distances.

7.2.1 L_p Distances

Consider two vectors $a = (a_1, a_2, \ldots, a_d)$ and $b = (b_1, b_2, \ldots, b_d)$ in $\mathbb{R}^d$. Now an L_p distances is defined as

$$\mathbf{d}_p(a, b) = \|a - b\|_p = \left(\sum_{i=1}^{d} (|a_i - b_i|)^p\right)^{1/p}.$$

1. The most common is the L_2 distance

$$\mathbf{d}_2(a, b) = \|a - b\| = \|a - b\|_2 = \sqrt{\sum_{i=1}^{d} (a_i - b_i)^2}.$$

   It easy interpreted as the *Euclidean* or "straight-line" distance between two points or vectors, since if you draw a line between two points, its length measures the Euclidean distance.
   It is also the only L_p distance that is invariant to the rotation of the coordinate system (which will be often be useful, but sometimes restrictive).

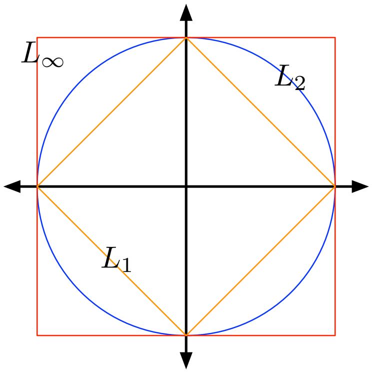

Figure 7.1: Unit balls in $\mathbb{R}^2$ for the L_1, L_2, and L_∞ distance.

2. Another common distance is the L_1 distance

$$\mathbf{d}_1(a,b) = \|a-b\|_1 = \sum_{i=1} |a_i - b_i|.$$

This is also known as the "Manhattan" distance since it is the sum of lengths on each coordinate axis; the distance you would need to walk in a city like Manhattan since must stay on the streets and can't cut through buildings. (Or in this class the "SLC distance.")
It is also amenable to LSH through 1-stable distributions (using Cauchy distribution $\frac{1}{\pi}\frac{1}{1+x^2}$ in place of the Gaussian distribution).

3. A common modeling goal is the L_0 distance

$$\mathbf{d}_0(a,b) = \|a-b\|_0 = d - \sum_{i=1}^{d} \mathbb{1}(a=b),$$

where $\mathbb{1}(a=b) = \begin{cases} 1 & \textbf{if } a=b \\ 0 & \textbf{if } a \neq b. \end{cases}$ Unfortunately, $\mathbf{d}_0$ is not convex.
When each coordinate a_i is either 0 or 1, then this is known as the *Hamming distance*.
There is no associated p-stable distribution, but can be approximated by a 0.001-stable distribution (but this is quite inefficient).

4. Finally, another useful variation is the L_∞ distance

$$\mathbf{d}_\infty(a,b) = \|a-b\|_\infty = \max_{i=1}^{d} |a_i - b_i|.$$

It is the maximum deviation along any one coordinate. Geometrically, it is a rotation of the L_1 distance, so many algorithms designed for L_1 can be adapted to L_∞.

All of these distances are metrics, and in general for L_p for $p \in [1,\infty)$. (M1) and (M2) hold since the distances are basically a sum of non-negative terms, and are only all 0 if all coordinates are identical. (M3) holds since $|a_i - b_i| = |b_i - a_i|$. (M4) is a bit trickier to show, but follows by drawing a picture $\ddot\smile$.

Figure 7.2.1 illustrates the unit balls for L_1, L_2, and L_∞. Note that the smaller the p value, the smaller the unit ball, and all touch the points a distance 1 from the origin along each axis. The L_0 ball is inside the L_1 ball, and in particular, for any $p < 1$, the L_p ball is *not* convex.

Warning about L_p Distance: These should *not* be used when the units on each coordinate are not the same. For instance, consider representing two people p_1 and p_2 as points in $\mathbb{R}^3$ where the x-coordinate represents height in inches, the y-coordinate represents weight in pounds, and the z-coordinate represents income in dollars per year. Then most likely this distance is dominated by the z-coordinate income which might vary on the order of 10,000 while the others vary on the order of 10.

Also, for the same data we could change the units, so the x-coordinate represents height in meters, the y-coordinate represents weight in centigrams, and the z-coordinate represents income in dollars per hour. The information may be exactly the same, only the unit changed. Its now likely dominated by the y-coordinate representing weight.

These sorts of issues can hold for distance other than L_p as well. A safe way is to avoid these issues is to use the L_0 metric – however this one can be crude and insensitive to small variations in data. Some heuristics to overcome this is: set hand-tuned scaling of each coordinate, ”normalize” the distance so they all have the same min and max value (e.g., all in the range $[0, 1]$), or ”normalize” the distance so they all have the same mean and variance. All of these are hacks and may have unintended consequences. For instance the $[0, 1]$ normalization is at the mercy of outliers, and mean-variance normalization can have strange effects in multi-modal distributions. *These are not solutions, they are hacks!*

With some additional information about which points are “close” or “far” one may be able to use the field of *distance metric learning* to address some of these problems. A simple solution can the be derived over all Mahalanobis distances (see below), using some linear algebra and gradient descent. But without this information, there is no one right answer. If you axes are the numbers of apples (x-axis) and number of oranges (y-axis), then its *literally comparing apples to oranges!*

7.2.2 Mahalanobis Distance

An extension to the L_2 distance is the *Mahalanobis* distance defined for two vectors $a, b \in \mathbb{R}^d$ and a $d \times d$ matrix M as

$$\mathbf{d}_M(a, b) = \sqrt{(a-b)^T M (a-b)}.$$

When $M = I$ (the identity matrix, so $I_{j,j} = 1$ and $I_{j,j'} = 0$ for $j \neq j'$), then $\mathbf{d}_M = \mathbf{d}_2$. This can be interpreted as skewing the Euclidean space (shrink some coordinates, and expanding others) based on the matrix M. The skew is defined through the eigenvectors and eigenvalues of M, as will be explained in more detail in L14. As long as all eigenvalues are positive and real (implying M is positive definite) then $\mathbf{d}_M$ is a metric; since then the skew is well-defined and full-dimensional.

7.2.3 Jaccard Distance

The Jaccard distance between two sets A and B is defined

$$\mathbf{d}_J(A, B) = 1 - \mathsf{JS}(A, B) = 1 - \frac{|A \cap B|}{|A \cup B|}.$$

We can see it is a metric. (M1) holds since the intersection size cannot exceed the union size. (M2) holds since $A \cap A = A \cup A = A$, and if $A \neq B$, then $A \cap B \subset A \cup B$. (M3) since $\cap$ and $\cup$ operations are symmetric. (M4) requires a bit more effort to show $\mathbf{d}_J(A, C) + \mathbf{d}_J(C, B) \geq \mathbf{d}_J(A, B)$.

Proof. We will use the notion that

$$\mathbf{d}_J(A, B) = 1 - \mathsf{JS}(A, B) = 1 - \frac{|A \cap B|}{|A \cup B|} = \frac{|A \triangle B|}{|A \cup B|}.$$

Next we assume that $C \subseteq A$ and $C \subseteq B$ since any elements in C but not in A or B will only increase the left-hand-side, but not the right-hand-side. If $C = A = B$ then $0 + 0 \geq 0$, otherwise we have

$$\begin{aligned}\mathbf{d}_J(A,C) + \mathbf{d}_J(C,B) &= \frac{|A \setminus C|}{|A|} + \frac{|B \setminus C|}{|B|} \\ &\geq \frac{|A \setminus C| + |B \setminus C|}{|A \cup B|} \\ &\geq \frac{|A \triangle B|}{|A \cup B|} = \mathbf{d}_J(A,B).\end{aligned}$$

The first inequality follows since $|A|, |B| \leq |A \cup B|$. The second inequality holds since anything taken out from A or B would be in $A \cup B$ and thus would not affect $A \triangle B$; it is only equal if $C = A \cup B$, and $A \triangle B = \emptyset$. □

7.2.4 Cosine Distance

This measures the cosine of the "angle" between vectors $a = (a_1, a_2, \ldots, a_d)$ and $b = (b_1, b_2, \ldots, b_d)$ in $\mathbb{R}^d$

$$\mathbf{d}_{\cos}(a,b) = 1 - \frac{\langle a, b \rangle}{\|a\| \|b\|} = 1 - \frac{\sum_{i=1}^d a_i b_i}{\|a\| \|b\|}.$$

Note that $\mathbf{d}(A,B) \in [0, \pi]$ and it does not depend on the magnitude $\|a\|$ of the vectors since this is normalized out. It only cares about their directions. This is useful when a vector of objects represent data sets of different sizes and we want to compare how similar are those distributions, but not their size. This makes it a psuedometric since for two vectors a and $a' = (2a_1, 2a_2, \ldots, 2a_d)$ where $\|a'\| = 2\|a\|$ have $\mathbf{d}_{\cos}(a, a') = 0$, but they are not equal.

(M1) and (M3) holds by definition. (M4) can be seen by considering the mapping of any vector $a \in \mathbb{R}^d$ to the $(d-1)$-dimensional sphere $\mathbb{S}^{d-1}$ as $a/\|a\|$. Then the cos distance describes the shortest geodesic distance on this sphere (or the shortest rotation from one to the other).

We can also develop an LSH function h for $\mathbf{d}_{\cos}$ as follows. Choose a random vector $v \in \mathbb{R}^d$. Then let

$$h_v(a) = \begin{cases} +1 & \text{if } \langle v, a \rangle > 0 \\ -1 & \text{otherwise} \end{cases}.$$

Is sufficient to make $v \in \{-1, +1\}^d$. The analysis is similar to for JS but in $[0, \pi]$ instead of $[0, 1]$. It is $(\gamma, \phi, (\pi - \gamma)/\pi, \phi/\pi)$-sensitive, for any $\gamma < \phi \in [0, \pi]$.

7.2.5 KL Divergence

The Kullback-Liebler Divergence (or KL Divergence) is a distance that is *not* a metric. Somewhat similar to the Cosine distance, it considers as input discrete distributions P and Q. The variable $P = (p_1, p_2, \ldots, p_d)$ is a set of non-negative values p_i such that $\sum_{i=1}^d p_i = 1$. That is, it describes a probability distribution over d possible values.

Then we can define (often written $\mathbf{d}_{KL}(P \| Q)$)

$$\mathbf{d}_{KL}(P,Q) = \sum_{i=1}^d p_i \ln(p_i / q_i).$$

It is reminiscent of entropy, and can be written as $H(P,Q) - H(P)$ where $H(P)$ is the entropy of P, and $H(P,Q)$ is the cross entropy. It roughly describes the extra bits needed to express a distribution P, given the knowledge of distribution Q.

Note that $\mathbf{d}_{KL}$ is *not* symmetric, violating (M3). It also violates the triangle inequality (M4).

7.2.6 Edit Distance

The edit distance considers two strings $a, b \in \Sigma^d$, and

$$\mathsf{d}_{\mathsf{ed}}(a, b) = \text{\# operations to make } a = b,$$

where an operation can delete a letter or insert a letter. Often Σ is the *alphabet* = {a, b, ..., z}.

Lets see an example with $a = \texttt{mines}$ and $b = \texttt{smiles}$. Here $\mathsf{d}_{\mathsf{ed}}(a, b) = 3$.

$$\begin{aligned} &\texttt{mines} \\ 1 : &\texttt{smines} \text{ insert } \texttt{s} \\ 2 : &\texttt{smies} \text{ delete } \texttt{n} \\ 3 : &\texttt{smiles} \text{ insert } \texttt{l} \end{aligned}$$

There are many alternative variations of operations. insert may cost more than delete. Or we could have a replace operation.

It is a metric. (M1) holds since the number of edits is always non-negative. (M2) There are no edits only if they are the same. (M3) the operations can be reversed. (M4) If c is an intermediate "word" then the $\mathsf{d}_{\mathsf{ed}}(a, c) + \mathsf{d}_{\mathsf{ed}}(c, b) = \mathsf{d}_{\mathsf{ed}}(a, b)$, otherwise it requires more edits.

Is this good for large text documents? Not really. It is slow. And removing one sentence can cause a large edit distance without changing meaning. But this *is* good for small strings. Some version used in most spelling recommendation systems (e.g. Google's auto-correct). Its a good guide that usually $\mathsf{d}_{\mathsf{ed}}(a, b) > 3$ is pretty large since, e.g., $\mathsf{d}_{\mathsf{ed}}(\texttt{cart}, \texttt{score}) = 4$.

There is a lot of work to approximate d_{ed} by some sort of L_1 distance so that it can be used in an LSH scheme. But as of now, there is not a good approximation, and this is hard to use with LSH (so its hard to find all close pairs quickly).

7.2.7 Graph Distance

Another important type of distance is the hop distance on a graph. A graph is a structure we will visit in more detail later on. Consider a series of vertices $V = \{v_1, v_2, \ldots, v_n\}$ and a series of edges $E = \{e_1, e_2, \ldots, e_m\}$. Each edge $e = \{v_i, v_i\}$ is a pair of vertices. Here consider only unordered pairs (so the graph is not directed). The set $G = (V, E)$ defines a graph.

Now the distance d_G between two vertices $v_i, v_j \in V$ in a graph G, is the fewest number of edges needed so there is a path $\langle v_i, v_1, v_2, \ldots, v_{k-1}, v_j \rangle$ so every consecutive pair $\{v_\ell, v_{\ell+1}\} \in E$, where v_i corresponds with v_ℓ with $\ell = 0$ and v_j corresponds with v_ℓ where $\ell = k$. So here the length of the path is k, and if this is the shortest such path, then the length $\mathsf{d}_G(v_i, v_j) = k$.

The hop distance in a graph is a metric. Its clearly non-negative (M1), is only 0 if $v_i = v_j$ (M2), and can be reversed (M3). To see the triangle inequality, assume that otherwise there is a node $c \in V$ such that $\mathsf{d}_G(v_i, c) + \mathsf{d}_G(c, v_j) < \mathsf{d}_G(v_i, v_j)$, then we could instead create a path from v_i to v_j that went though c, and by transitivity, in the above equation the left-hand-side must be at least as large as the right-hand-side.