

Lecture 6: Random Projections

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We will give a simple proof of the following, rather amazing, fact. Every set of n points in a Euclidian space (say in dimension d) can be embedded into the Euclidian space of dimension $O(\log(n)/\varepsilon^2)$ such that all pairwise distances are preserved up to distortion $1 \pm \varepsilon$.

Random projection

We will argue that a certain distribution over the choice of a matrix $R \in \mathbb{R}^{k \times d}$ gives that:

$$\forall x \in \mathbb{R}^d \quad \Pr \left[\left| \left\| \frac{1}{\sqrt{k}} Rx \right\| - \|x\| \right| > \varepsilon \|x\| \right] \leq \frac{1}{n^2} \quad (1)$$

Before we show this distribution and show that Equation 1 holds for it, let us first see that this will give the opening statement.

Consider a set of n points x_1, \dots, x_n in Euclidian space \mathbb{R}^d . Embedding these points into a lower dimension while preserving all distances between them up to distortion $1 \pm \varepsilon$ means approximately preserving the norms of all $\binom{n}{2}$ vectors $x_i - x_j$. Assuming Equation 1 holds and using the union bound, this property will fail to hold for at least one $x_i - x_j$ pair with probability at most $\binom{n}{2} \frac{1}{n^2} \leq 1/2$. Which means that all $\binom{n}{2}$ point distances are preserved up to distortion ε with probability at least $1/2$.

1 I.i.d gaussian distribution

We consider the distribution of matrices R such that each $R(i, j)$ is drawn independently from a normal distribution with mean zero and variance 1, $R(i, j) \sim \mathcal{N}(0, 1)$. We will show that for this distribution Equation 1 holds for some $k \in O(\log(n)/\varepsilon^2)$.

First consider the random variable $z = \sum_{i=1}^d r(i)x(i)$ where $r(i) \sim \mathcal{N}(0, 1)$. To understand how the variable z distributes we recall the two-stability of the normal distribution. Namely, if $z_3 = z_2 + z_1$ and $z_1 \sim \mathcal{N}(\mu_1, \sigma_1^2)$ and $z_2 \sim \mathcal{N}(\mu_2, \sigma_2^2)$ then, $z_3 \sim \mathcal{N}(\mu_1 + \mu_2, \sigma_1^2 + \sigma_2^2)$. In our case, $r(i)x(i) \sim \mathcal{N}(0, x_i^2)$ and therefore, $z = \sum_{i=1}^d r(i)x(i) \sim \mathcal{N}(0, \sum_{i=1}^d x_i^2) = \mathcal{N}(0, \|x\|^2) = \|x\| \cdot \mathcal{N}(0, 1)$. Now, note that each element in the vector Rx distributes exactly like z . Defining k identical copies of z , z_1, \dots, z_k , We get that $\|\frac{1}{\sqrt{k}} Rx\|$ distributes exactly like:

$$\left\| \frac{1}{\sqrt{k}} Rx \right\| \sim \sqrt{\frac{1}{k} \sum_{i=1}^k z_i^2} \sim \|x\| \sqrt{\frac{1}{k} \sum_{i=1}^k y_i^2}$$

where $y_i \sim \mathcal{N}(0, 1)$. Thus, proving Equation 1 reduces to showing that:

$$\Pr \left[\left| \sqrt{\frac{1}{k} \sum_{i=1}^k y_i^2} - 1 \right| > \varepsilon \right] \leq \frac{1}{n^2} \quad (2)$$

It is now straight forward to show since the sum of k squared normal variables is a very known distribution called chi-square with k degrees of freedom. (χ_k^2). More accurately, it is defined by $\chi_k^2 = \sum_{i=1}^k y_i^2$ where $y_i \sim \mathcal{N}(0, 1)$ which is exactly what we have. Since χ_k^2 is a sum of independent random variables, due to the central limit theorem, χ_k^2 converges to a normally distributed quantity as k grows. We will use here a slightly different property: $\sqrt{\chi_k^2} \sim_{k \rightarrow \infty} \mathcal{N}(\sqrt{k}, 1/2)$. Somewhat sloppily, we will assume that k is large enough so that assuming $\sqrt{\chi_k^2} \sim \mathcal{N}(\sqrt{k-1/2}, 1/2) \approx \mathcal{N}(\sqrt{k}, 1/2)$ is harmless. In that case, $\sqrt{\frac{1}{k} \sum_{i=1}^k y_i^2} \sim \mathcal{N}(1, \frac{1}{2k})$ and $\sqrt{\frac{1}{k} \sum_{i=1}^k y_i^2} - 1 \sim \mathcal{N}(0, \frac{1}{2k})$. Thus, we only need to show that for a random variable $Z \sim \sqrt{2k} \left[\sqrt{\frac{1}{k} \sum_{i=1}^k y_i^2} - 1 \right] \sim \sqrt{2k} \mathcal{N}(0, \frac{1}{2k}) \sim \mathcal{N}(0, 1)$ it holds that

$$\Pr \left[|Z| > \varepsilon \sqrt{2k} \right] \leq \frac{1}{n^2} \quad (3)$$

We now use a bound on the error function: $\int_{t=\varepsilon\sqrt{2k}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt = \text{erf}(\varepsilon\sqrt{2k}) \leq e^{-\varepsilon^2 k}$. Since $\Pr[Z > \varepsilon\sqrt{2k}] = \Pr[Z < -\varepsilon\sqrt{2k}]$ we demand that $e^{-\varepsilon^2 k} \leq \frac{1}{2n^2}$. This yields the bound $k \geq \frac{2\log(n)+1}{\varepsilon^2}$.