COMPSCI 514: ALGORITHMS FOR DATA SCIENCE

Cameron Musco

University of Massachusetts Amherst. Spring 2020.

Lecture 12

- Problem Set 2 is due this upcoming Sunday 3/8 at 8pm.
- Midterm is next Thursday, 3/12. See webpage for study guide/practice questions.
- I will hold office hours **after class today**.
- Next week office hours will be at the usual time after class Tuesday and also **before class at 10:00am**.

Last Class: Finished Up Johnson-Lindenstrauss Lemma

- Completed the proof of the Distributional JL lemma.
- Showed two applications of random projection: faster support vector machines and k-means clustering.
- Started discussion of high-dimensional geometry.

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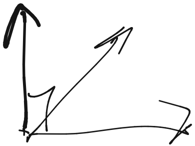
This Class: High-Dimensional Geometry

- Bizarre phemomena in high-dimensional space.
- Connections to JL lemma and random projection.

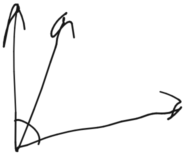
What is the largest set of mutually orthogonal unit vectors in d-dimensional space? Answer: d.



What is the largest set of mutually orthogonal unit vectors in d-dimensional space? Answer: d.

What is the largest set of unit vectors in d-dimensional space that have all pairwise dot products $|\langle \vec{x}, \vec{y} \rangle| \leq \epsilon$? (think $\epsilon = .01$)
Answer: $2^{\Theta(\epsilon^2 d)}$. $= 2^{\Theta(d)}$

$2^{d/1000}$



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In fact, an exponentially large set of random vectors will be nearly pairwise orthogonal with high probability!

Claim: $2^{\Theta(\epsilon^2 d)}$ random d-dimensional unit vectors will have all pairwise dot products $|\langle \vec{x}, \vec{y} \rangle| \leq \epsilon$ (be nearly orthogonal).

$t =$

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✓ • What is $\|\vec{x}_i\|_2$? $= \sqrt{\sum_{j=1}^{d} x_i(j)^2} = \sqrt{\sum_{j=1}^{d} 1/d} = \sqrt{1} = 1$

✓ • What is $\mathbb{E}[\langle \vec{x}_i, \vec{x}_j \rangle]$? $= 0$

$$\mathbb{E}\langle x_i, x_j \rangle = \sum_{k=1}^{d} \mathbb{E}[x_i(k)\, x_j(k)] = \sum_{k=1}^{d} 0 = 0$$

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Proof: Let $\vec{x}_1, \ldots, \vec{x}_t$ each have independent random entries set to $\pm 1/\sqrt{d}$.

- What is $\|\vec{x}_i\|_2$? Every $\vec{x}_i$ is always a unit vector.
- What is $\mathbb{E}[\langle \vec{x}_i, \vec{x}_j \rangle]$?

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- By a Chernoff bound, $\Pr[|\langle \vec{x}_i, \vec{x}_j \rangle| \ge \epsilon] \le \boxed{2e^{-\epsilon^2 d/6}}$.

$$\sum_{k=1}^{d} \underbrace{x_i(k)\, x_j(k)}_{+\frac{1}{d} \quad -\frac{1}{d}}$$

$\frac{d}{2}$ 1 $\frac{d}{2}$ 0

$\{0, 1\}$

$t = \#$ random vectors $\quad (e^x)^2 = e^{2x}$

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- If we chose $t = \frac{1}{2}e^{\epsilon^2 d/12}$, using a union bound over all $\binom{t}{2} \leq \frac{1}{8}e^{\epsilon^2 d/6}$ possible pairs, with probability $\geq 3/4$ all will be nearly orthogonal.

$\binom{t}{2} = \frac{t(t-1)}{2} \leq \frac{t^2}{2}$

$\frac{t^2}{2} = \frac{\frac{1}{4}e^{\varepsilon^2 d/6}}{2} = \frac{1}{8}e^{\varepsilon^2 d/6}$

$\Pr(\text{any pair is not nearly orthogonal}) \leq \frac{1}{8}e^{\varepsilon^2 d/6} \cdot 2e^{-\varepsilon^2 d/6} = \frac{1}{4}$

Up Shot: In d-dimensional space, a set of $2^{\Theta(\epsilon^2 d)}$ random unit vectors have all pairwise dot products at most ϵ (think $\epsilon = .01$) with good probability.

$\Pr(\text{all } \binom{t}{2} \text{ pairs are nearly orth.}) > \frac{3}{4}$

$t = \frac{1}{2} e^{\epsilon^2 d/12} = 2^{\Theta(\epsilon^2 d)}$

Up Shot: In d-dimensional space, a set of $2^{\Theta(\epsilon^2 d)}$ random unit vectors have all pairwise dot products at most ϵ (think $\epsilon = .01$)

$$\|\vec{x}_i - \vec{x}_j\|_2^2$$

Up Shot: In d-dimensional space, a set of $2^{\Theta(\epsilon^2 d)}$ random unit vectors have all pairwise dot products at most ϵ (think $\epsilon = .01$)

$$\|\vec{x}_i - \vec{x}_j\|_2^2 = \|\vec{x}_i\|_2^2 + \|\vec{x}_j\|_2^2 - 2\vec{x}_i^T\vec{x}_j$$

$$1 \quad + \quad 1 - 2\epsilon$$

CURSE OF DIMENSIONALITY

Up Shot: In d-dimensional space, a set of $2^{\Theta(\epsilon^2 d)}$ random unit vectors have all pairwise dot products at most ϵ (think $\epsilon = .01$)

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≤ 2.02

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$\underline{2^d}$

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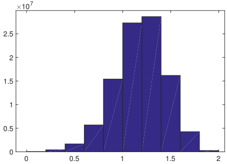
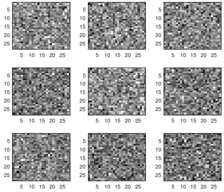
Curse of dimensionality for sampling/learning functions in high-dimensional space – samples are very 'sparse' unless we have a huge amount of data.

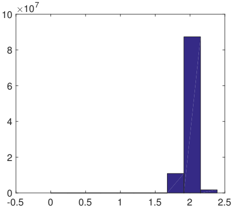
- Only hope is if we lots of structure (which we typically do...)

Distances for MNIST Digits:



Distances for Random Images:





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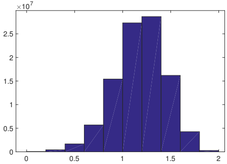

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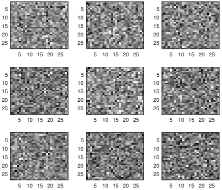

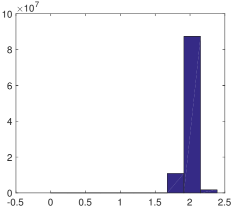

Another Interpretation: Tells us that random data can be a very bad model for actual input data.

Recall: The Johnson Lindenstrauss lemma states that if $\mathbf{\Pi} \in \mathbb{R}^{m \times d}$ is a random matrix (linear map) with $m = O\left(\frac{\log n}{\epsilon^2}\right)$, for $\vec{x}_1, \ldots, \vec{x}_n \in \mathbb{R}^d$ with high probability, for all i, j:

$$(1-\epsilon)\|\vec{x}_i - \vec{x}_j\|_2^2 \leq \|\mathbf{\Pi}\vec{x}_i - \mathbf{\Pi}\vec{x}_j\|_2^2 \leq (1+\epsilon)\|\vec{x}_i - \vec{x}_j\|_2^2.$$

CONNECTION TO DIMENSIONALITY REDUCTION

Recall: The Johnson Lindenstrauss lemma states that if $\mathbf{\Pi} \in \mathbb{R}^{m \times d}$ is a random matrix (linear map) with $m = O\left(\frac{\log n}{\epsilon^2}\right)$, for $\vec{x}_1, \ldots, \vec{x}_n \in \mathbb{R}^d$ with high probability, for all i, j:

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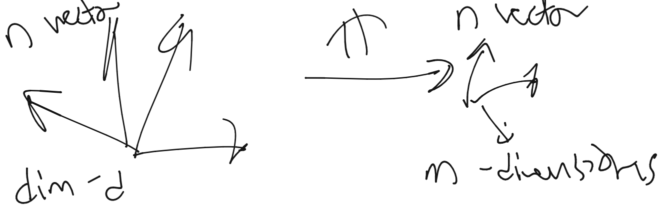
Implies: If $\vec{x}_1, \ldots, \vec{x}_n$ are nearly orthogonal unit vectors in d-dimensions (with pairwise dot products bounded by $\epsilon/8$), then $\frac{\mathbf{\Pi}\vec{x}_1}{\|\mathbf{\Pi}\vec{x}_1\|_2}, \ldots, \frac{\mathbf{\Pi}\vec{x}_n}{\|\mathbf{\Pi}\vec{x}_n\|_2}$ are nearly orthogonal unit vectors in m-dimensions (with pairwise dot products bounded by ϵ).



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- Similar to SVM analysis. Algebra is a bit messy but a good exercise to partially work through.

in d dimensions

Claim 1: n nearly orthogonal unit vectors can be projected to $m = O\left(\frac{\log n}{\epsilon^2}\right)$ dimensions and still be nearly orthogonal.

Claim 2: In m dimensions, there are at most $2^{O(\epsilon^2 m)}$ nearly orthogonal vectors.

lets me produce n near orthogonal vecs. in m dimensions

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Claim 2: In m dimensions, there are at most $2^{O(\epsilon^2 m)}$ nearly orthogonal vectors. → I can't have more than $2^{\epsilon^2 m}$ in m dimension

- For both these to hold it ~~might~~ must be that $n \leq 2^{O(\epsilon^2 m)}$.

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- $2^{O(\epsilon^2 m)} = 2^{O(\log n)} \geq n$. Tells us that the JL lemma is optimal up to constants.

$2^{\varepsilon^2 m}$ $\quad$ $m = \frac{\log n}{\varepsilon^2 \cdot 10}$

$n = 2^{\varepsilon^2 m} = 2^{\frac{\log n}{10}} < n$

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- For both these to hold it might be that $n \leq 2^{O(\epsilon^2 m)}$.
- $2^{O(\epsilon^2 m)} = 2^{O(\log n)} \leq n$. Tells us that the JL lemma is optimal up to constants.
- m is chosen just large enough so that the odd geometry of d-dimensional space still holds on the n points in question after projection to a much lower dimensional space.

Let $\mathcal{B}_d$ be the unit ball in d dimensions. $\mathcal{B}_d = \{x \in \mathbb{R}^d : \|x\|_2 \leq 1\}$.

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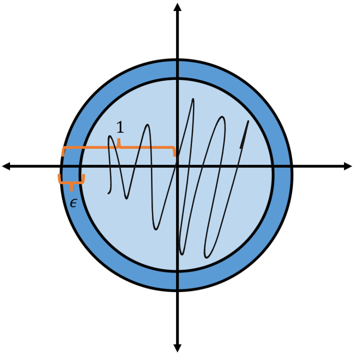
What percentage of the volume of $\mathcal{B}_d$ falls within ϵ distance of its surface?



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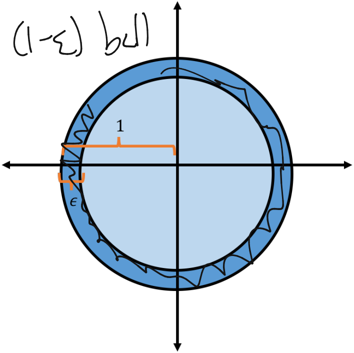
$R^d = 1$

Volume radius 1 ball

− Volume radius $(1-\epsilon)$ ball

$R^d = \underline{(1-\epsilon)^d}$



Volume of a radius R ball is $\frac{\pi^{\frac{d}{2}}}{(d/2)!} \cdot R^d$.

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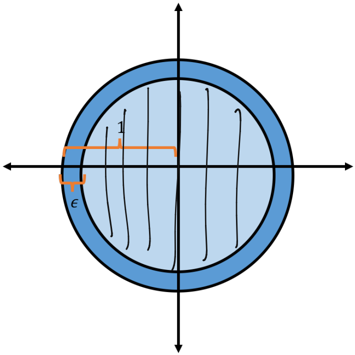
What percentage of the volume of $\mathcal{B}_d$ falls within ϵ distance of its surface? Answer: all but a $(1-\epsilon)^d \leq e^{-\epsilon d}$ fraction. Exponentially small in the dimension d!



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BIZARRE SHAPE OF HIGH-DIMENSIONAL BALLS

All but an $e^{-\epsilon d}$ fraction of a unit ball's volume is within ϵ of its surface. If we randomly sample points with $\|x\|_2 \leq 1$, nearly all will have $\|x\|_2 \geq 1 - \epsilon$.

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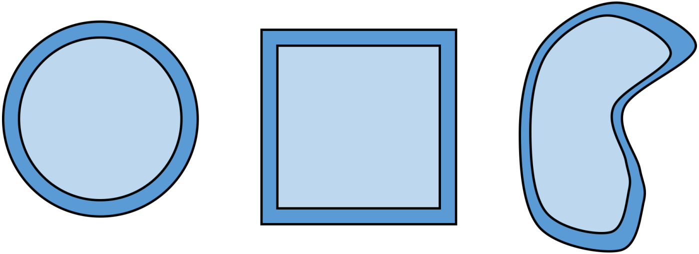
minimum

- **Isoperimetric inequality**: the ball has the ~~maximum~~ surface area/volume ratio of any shape.



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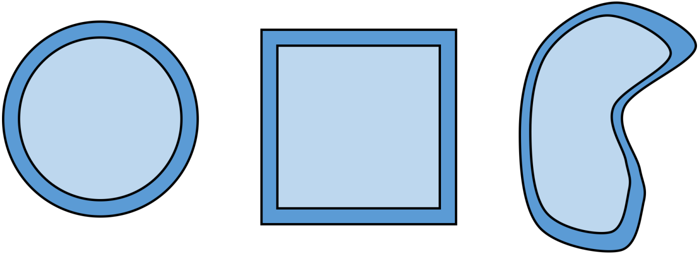

- If we randomly sample points from any high-dimensional shape, nearly all will fall near its surface.

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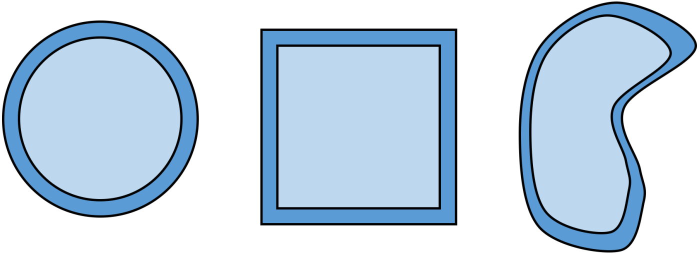
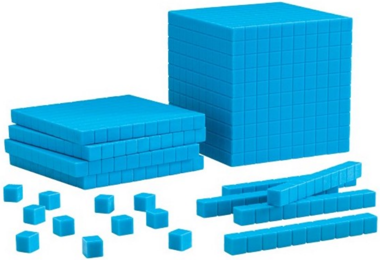


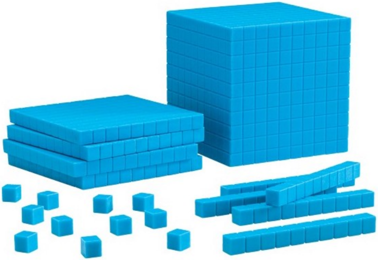
- If we randomly sample points from any high-dimensional shape, nearly all will fall near its surface.
- 'All points are outliers.'

What fraction of the cubes are visible on the surface of the cube? $\frac{1}{2}$



What fraction of the cubes are visible on the surface of the cube?

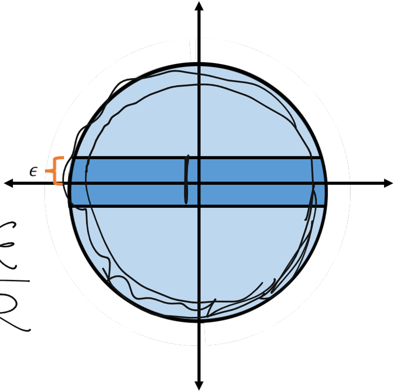
$20^3 - 18^3 =$



$$\frac{10^3 - 8^3}{10^3} = \frac{1000 - 512}{1000} = .488 \approx 1/2$$

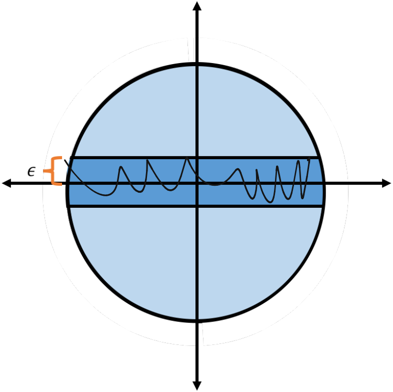
What percentage of the volume of $\mathcal{B}_d$ falls within ϵ distance of its equator?

$$\frac{\epsilon R^{d-1}}{R^d} = \frac{\epsilon}{R}$$



Formally: volume of set $S = \{x \in \mathcal{B}_d : |x(1)| \leq \epsilon\}$.

What percentage of the volume of $\mathcal{B}_d$ falls within ϵ distance of its equator? Answer: all but a $2^{\Theta(-\epsilon^2 d)}$ fraction.



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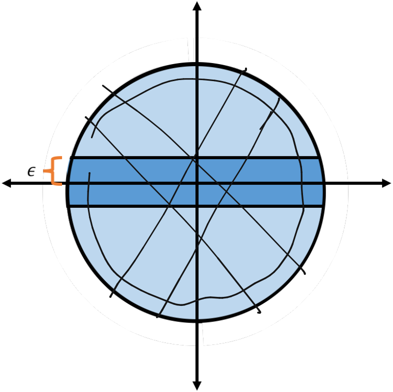

Formally: volume of set $S = \{x \in \mathcal{B}_d : |x(1)| \leq \epsilon\}$.

By symmetry, all but a $2^{\Theta(-\epsilon^2 d)}$ fraction of the volume falls within ϵ of any equator! $S = \{x \in \mathcal{B}_d : |\langle x, t\rangle| \leq \epsilon\}$

Claim 1: All but a $2^{\Theta(-\epsilon^2 d)}$ fraction of the volume of a ball falls within ϵ of any equator.

Claim 2: All but a $2^{\Theta(-\epsilon d)}$ fraction falls within ϵ of its surface.

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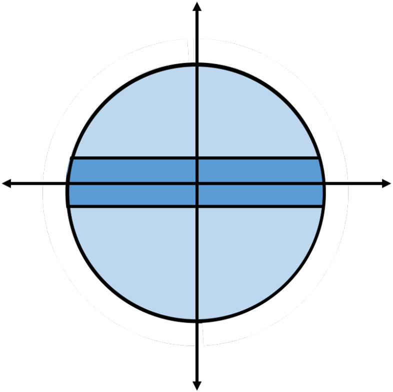

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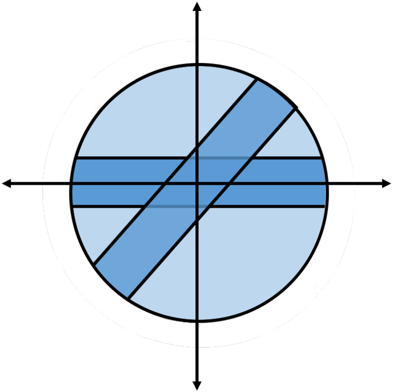

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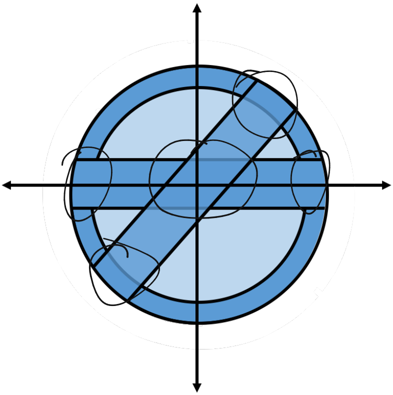

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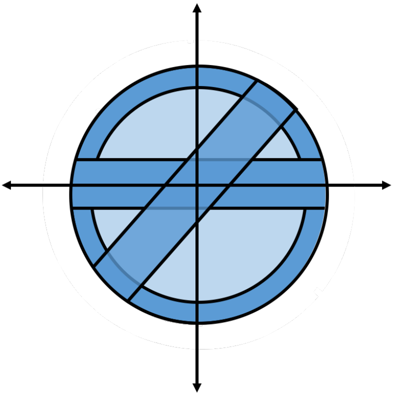

How is this possible?

BIZARRE SHAPE OF HIGH-DIMENSIONAL BALLS

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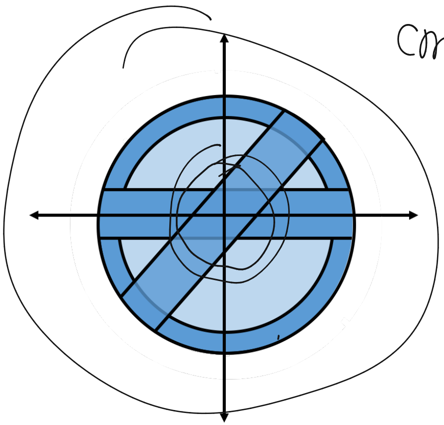
$B(R/2)$

$B((1-\varepsilon)R/2)$



Concentration of measure.

How is this possible? High-dimensional space looks nothing like this picture!

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- $\bar{x}(1) = \frac{x(1)}{\|x\|_2}$. What is $\mathbb{E}[\|x\|_2^2]$?

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$$\begin{aligned}\Pr[|\bar{x}(1)| > \epsilon] &= \Pr[|x(1)| > \epsilon \cdot \|x\|_2] \\ &\leq Pr[|x(1)| > \epsilon \cdot \sqrt{d/2}]\end{aligned}$$

CONCENTRATION OF VOLUME AT EQUATOR

Claim: All but a $2^{\Theta(-\epsilon^2 d)}$ fraction of the volume of a ball falls within ϵ of its equator. I.e., in $S = \{x \in \mathcal{B}_d : |x(1)| \leq \epsilon\}$.

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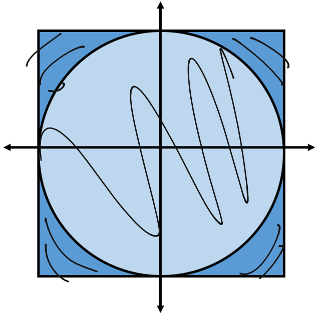
In low-dimensions, the cube is not that different from the ball.



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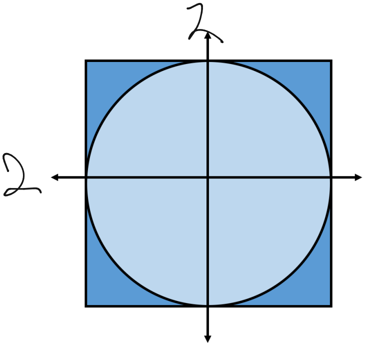

But volume of $\mathcal{C}_d$ is 2^d while volume of $\mathcal{B}^d$ is $\frac{\pi^{\frac{d}{2}}}{(d/2)!} = \frac{1}{d^{\Theta(d)}}$. A huge gap!

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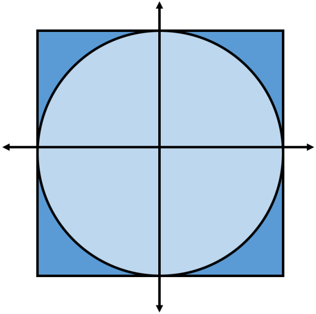
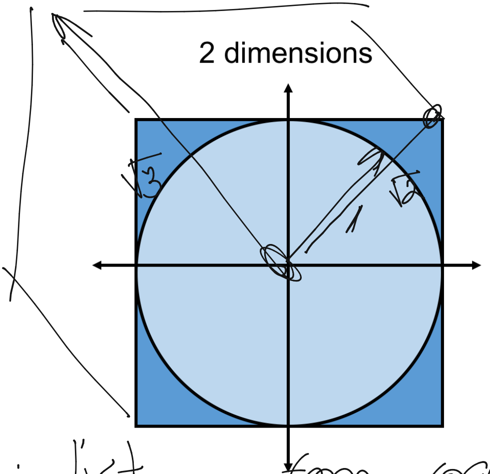
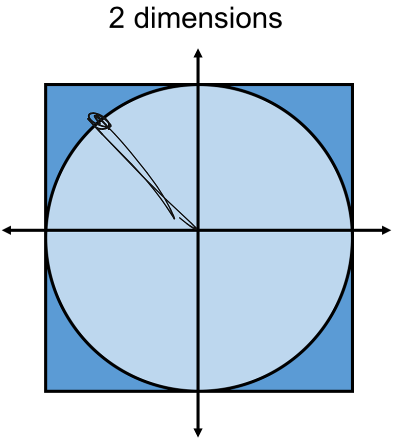


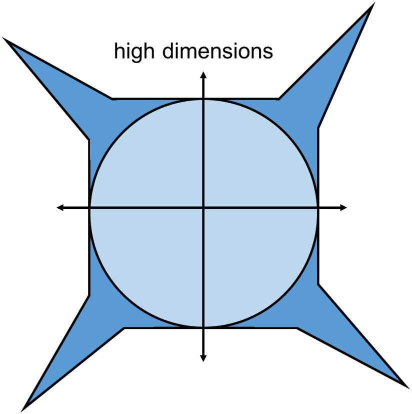
But volume of $\mathcal{C}_d$ is 2^d while volume of $\mathcal{B}^d$ is $\frac{\pi^{\frac{d}{2}}}{(d/2)!} = \frac{1}{d^{\Theta(d)}}$. A huge gap! So something is very different about these shapes...



$\sqrt{d}$: distance from corner to center



Corners of cube are $\sqrt{d}$ times further away from the origin than the surface of the ball.



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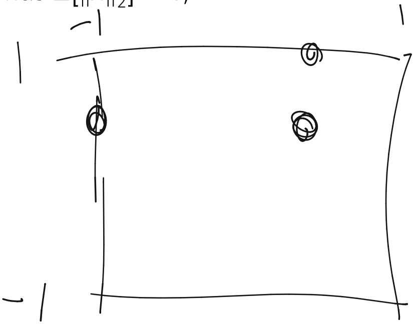
- $x \sim \mathcal{C}_d$ has $\mathbb{E}[\|x\|_2^2] = ?$,



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- $x \sim \mathcal{B}_d$ has $\|x\|_2^2 \leq 1$.
- $x \sim \mathcal{C}_d$ has $\mathbb{E}[\|x\|_2^2] = d/3$,

$$\mathbb{E}\|x\|_2^2 = \sum_{i=1}^{d} \mathbb{E}\, x(i)^2 = \sum_{i=1}^{d} \frac{1}{3} = \frac{d}{3}$$

HIGH-DIMENSIONAL CUBES

Data generated from the ball $\mathcal{B}_d$ will behave very differently than data generated from the cube $\mathcal{C}_d$.

- $x \sim \mathcal{B}_d$ has $\|x\|_2^2 \leq 1$.
- $x \sim \mathcal{C}_d$ has $\mathbb{E}[\|x\|_2^2] = d/3$, and $\Pr[\|x\|_2^2 \leq d/6] \leq 2^{-\Theta(d)}$.

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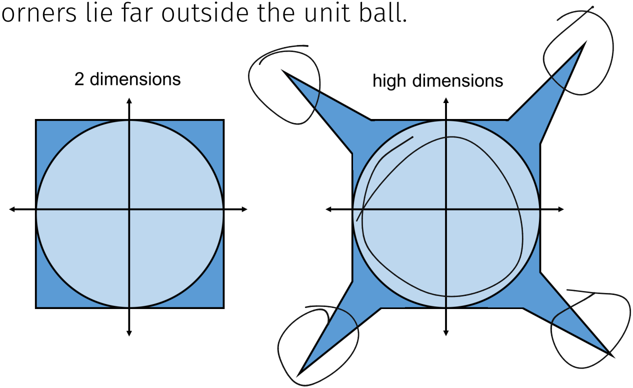
- $x \sim \mathcal{B}_d$ has $\|x\|_2^2 \leq 1$.
- $x \sim \mathcal{C}_d$ has $\mathbb{E}[\|x\|_2^2] = d/3$, and $\Pr[\|x\|_2^2 \leq d/6] \leq 2^{-\Theta(d)}$.
- Almost all the volume of the unit cube falls in its corners, and these corners lie far outside the unit ball.



TAKAWAYS

- High-dimensional space behaves very differently from low-dimensional space.
- Random projection (i.e., the JL Lemma) reduces to a much lower-dimensional space that is still large enough to capture this behavior on a subset of n points.
- Need to be careful when using low-dimensional intuition for high-dimensional vectors.
- Need to be careful when modeling data as random vectors in high-dimensions.