

CS5275 – The Algorithm Designer's Toolkit
(S2 AY2025/26)

Lecture 3:

Expanders – metric embedding

Our goal: Proving Bourgain's theorem

Bourgain's theorem:

- Given any n -point metric space (X, d) ,
 - there is an embedding $f: X \rightarrow \mathbb{R}^{O(\log^2 n)}$ such that for any $x, y \in X$,
$$\|f(x) - f(y)\|_1 \leq d(x, y) \leq O(\log n) \cdot \|f(x) - f(y)\|_1$$

Algorithm

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Algorithm:

- Randomly sample $O(\log^2 n)$ subsets:
$$A_{i,j} \subseteq X \quad | \quad 1 \leq i \leq c \log n, \quad 1 \leq j \leq \log n$$
- Each point in X joins $A_{i,j}$ with probability 2^{-j} independently.
- Set $f_{i,j}(x) = d(x, A_{i,j}) = \min_{y \in A_{i,j}} d(x, y)$.

$$\|f(x) - f(y)\|_1 = \sum_{i,j} |f_{i,j}(x) - f_{i,j}(y)|$$

- For simplicity, assume $\log n$ is an integer.
- c is some constant.

Correctness

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 - there is an embedding $f: X \rightarrow \mathbb{R}^{O(\log^2 n)}$ such that for any $x, y \in X$,
 $\|f(x) - f(y)\|_1 \leq d(x, y) \cdot O(\log n)$

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$$\|f(x) - f(y)\|_1 = \sum_{i,j} |f_{i,j}(x) - f_{i,j}(y)|$$

Correctness:

With high probability, we have:

- Part 1:** $\sum_{i,j} |f_{i,j}(x) - f_{i,j}(y)| \leq d(x, y) \cdot c \log^2 n$
- Part 2:** $\sum_{i,j} |f_{i,j}(x) - f_{i,j}(y)| \in d(x, y) \cdot \Omega(\log n)$

With a scaling $f_{i,j}(x) \leftarrow f_{i,j}(x) \cdot \frac{1}{c \log^2 n}$,
this proves Bourgain's theorem.

Correctness: Part 1

Without loss of generality, assume $d(x, A_{i,j}) \geq d(y, A_{i,j})$

Triangle inequality

$$\begin{aligned} |f_{i,j}(x) - f_{i,j}(y)| &= |d(x, A_{i,j}) - d(y, A_{i,j})| \\ &= d(x, A_{i,j}) - d(y, A_{i,j}) \\ &\leq (d(x, y) + d(y, A_{i,j})) - d(y, A_{i,j}) \\ &= d(x, y) \end{aligned}$$

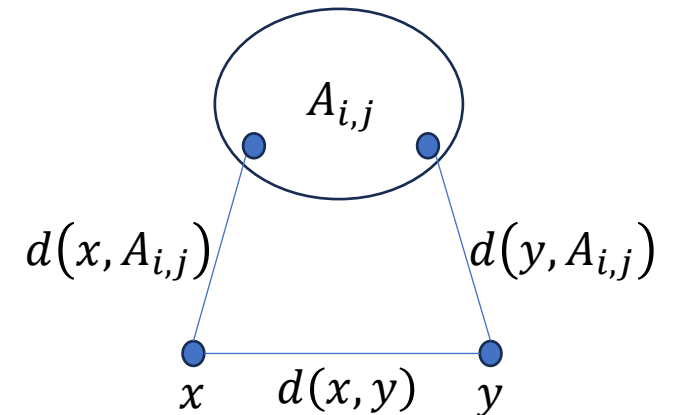
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Correctness: Part 2

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Next

Main tool: Chernoff bound

- Consider the following setting.
 - X_1, X_2, \dots, X_n are independent random variables taking values in $\{0, 1\}$.
 - $X = \sum_{i=1}^n X_i$.
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Chernoff bounds:

- $\Pr[X \geq (1 + \delta)\mu] \leq e^{-\frac{\delta^2 \mu}{3}}, \quad \text{for } 1 \geq \delta \geq 0.$
- $\Pr[X \geq (1 + \delta)\mu] \leq e^{-\frac{\delta^2 \mu}{2 + \delta}}, \quad \text{for } \delta \geq 0.$
- $\Pr[X \leq (1 - \delta)\mu] \leq e^{-\frac{\delta^2 \mu}{2}}, \quad \text{for } 1 \geq \delta \geq 0.$

https://en.wikipedia.org/wiki/Chernoff_bound

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Key takeaway:

- X is within a constant factor of $\mathbb{E}[X]$ with a probability of $1 - e^{-\Omega(\mathbb{E}[X])}$.
- In particular, $\mathbb{E}[X] \in \Omega(c \log n)$ guarantees a success probability of $1 - n^{-\Omega(c)}$.

Correctness: Part 2

- $B(v, r)$ = the ball of radius r around v .
- $B(v, < r)$ = the open ball of radius r around v .

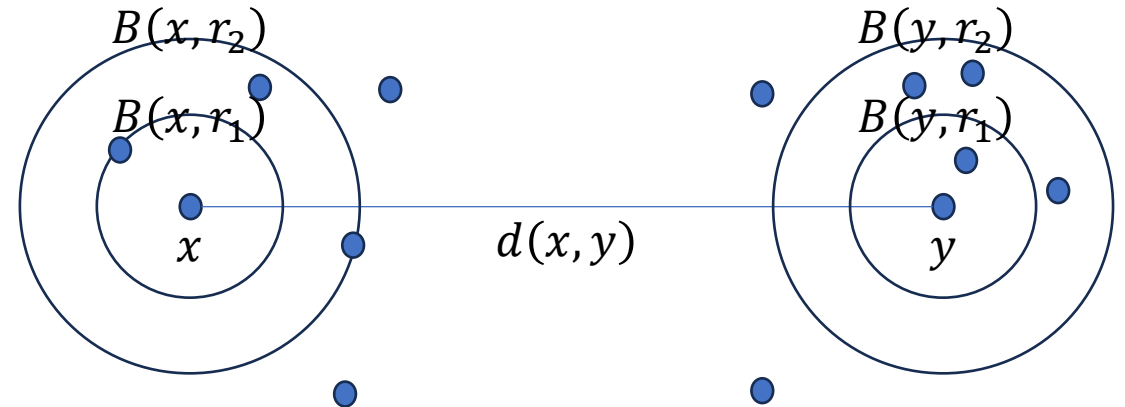
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Consider two points x and y in X .

r_j = the minimum of:

- Smallest number r such that $\min\{|B(x, r)|, |B(y, r)|\} \geq 2^j$
- $\frac{d(x, y)}{3}$



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Observation 1:

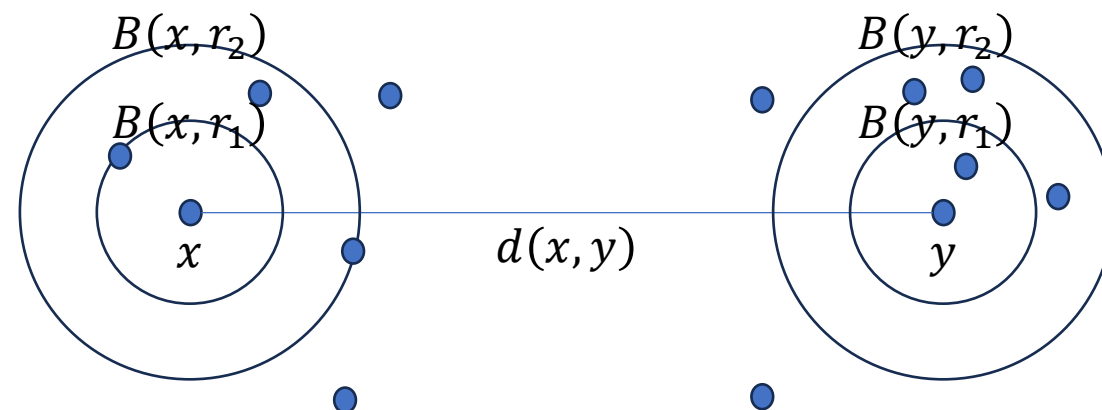
$$|B(x, < r_j)| < 2^j \text{ or } |B(y, < r_j)| < 2^j$$

Without loss of generality, we assume this.

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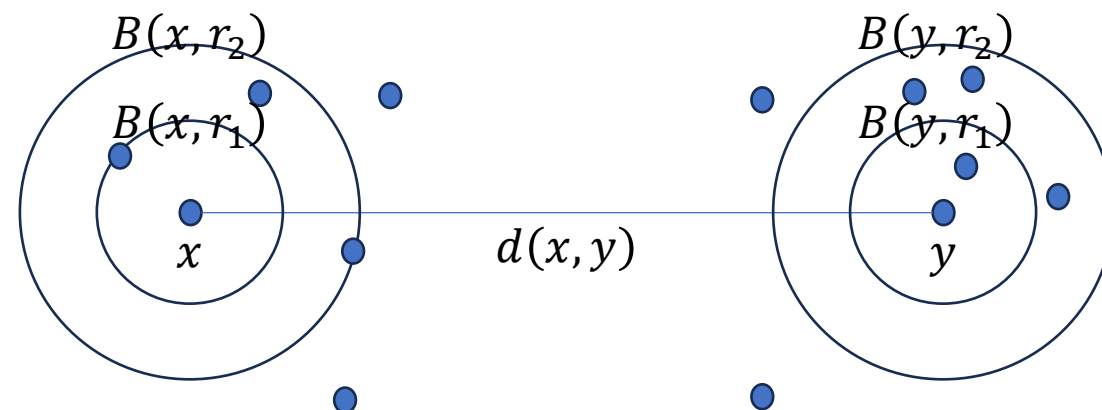
If $r_{j-1} < \frac{d(x,y)}{3}$, then

$$|B(x, r_{j-1})| \geq 2^{j-1} \text{ and } |B(y, r_{j-1})| \geq 2^{j-1}$$

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Suppose $r_{j-1} < \frac{d(x,y)}{3}$.

Let $\mathcal{E}_{i,j}$ be the event that:

- $B(x, < r_j) \cap A_{i,j} = \emptyset$
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For $n \geq 2$, we have: $\left(1 - \frac{1}{n}\right)^n \geq \left(1 - \frac{1}{2}\right)^2 = \frac{1}{4}$

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Let $\mathcal{E}_{i,j}$ be the event that:

- $B(x, < r_j) \cap A_{i,j} = \emptyset$
 - Probability = $\left(1 - \frac{1}{2^j}\right)^{|B(x, < r_j)|} > \left(1 - \frac{1}{2^j}\right)^{2^j} \geq \frac{1}{4}$
- $B(y, r_{j-1}) \cap A_{i,j} \neq \emptyset$
 - Probability = $1 - \left(1 - \frac{1}{2^j}\right)^{|B(y, r_{j-1})|}$

$$\geq 1 - \left(1 - \frac{1}{2^j}\right)^{2^{j-1}} \geq 1 - e^{-1/2} \geq \frac{1}{3}$$

Claim 1: $\Pr[\mathcal{E}_{i,j}] > \frac{1}{12}$

$$1 + x \leq e^x$$

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Claim 2: If $\mathcal{E}_{i,j}$ occurs, then:

- $|f_{i,j}(x) - f_{i,j}(y)| \geq r_j - r_{j-1}$

Correctness: Part 2

- Consider the following setting.
 - $X_i \in \{0,1\}$ is the indicator random variable for the event $\mathcal{E}_{i,j}$.
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$$\Pr\left[X \leq \frac{c \log n}{24}\right] \leq \Pr\left[X \leq \frac{\mu}{2}\right] \leq e^{-\frac{\left(\frac{1}{2}\right)^2 \mu}{2}} \in n^{-\Omega(c)}$$

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With probability $1 - n^{-\Omega(c)}$, we have:

$$\sum_i |f_{i,j}(x) - f_{i,j}(y)| \geq (r_j - r_{j-1}) \cdot \frac{c \log n}{24}$$

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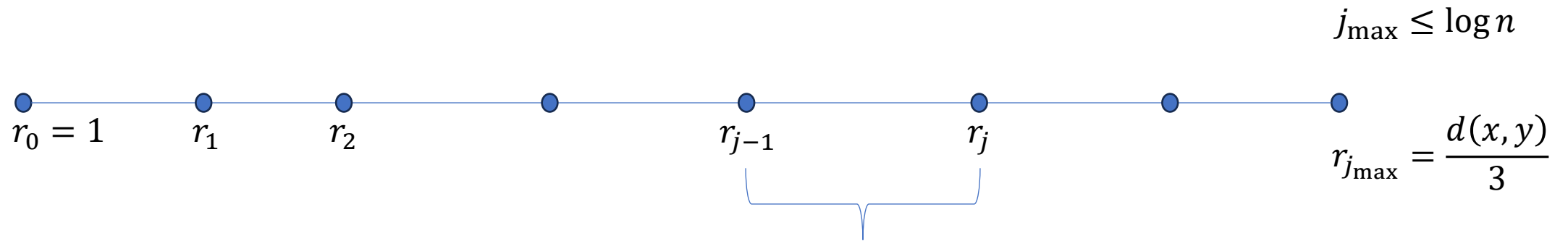
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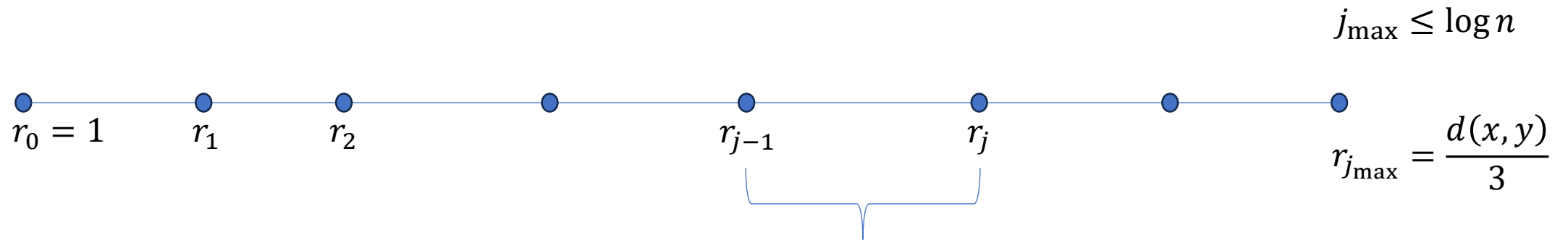
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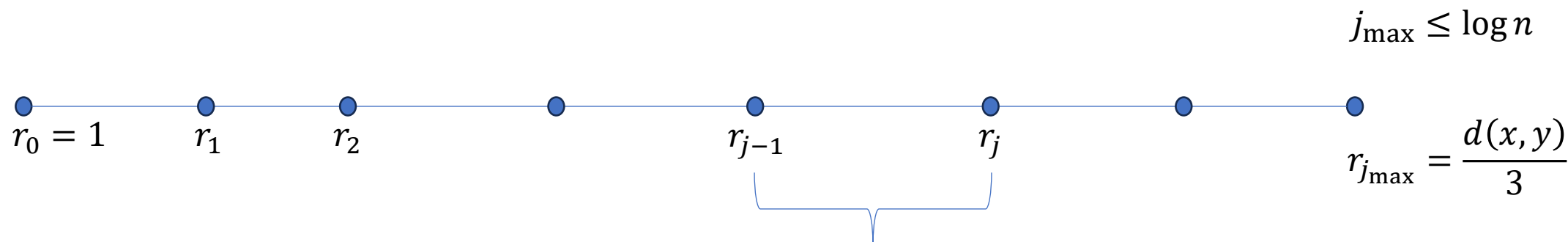
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With probability $1 - j_{\max} \cdot n^{-\Omega(c)}$, we have: $\sum_{i,j} |f_{i,j}(x) - f_{i,j}(y)| \geq \frac{d(x,y)}{3} \cdot \frac{c \log n}{24}$

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With probability $1 - \binom{n}{2} \cdot j_{\max} \cdot n^{-\Omega(c)}$, we have: $\sum_{i,j} |f_{i,j}(x) - f_{i,j}(y)| \geq \frac{d(x,y)}{3} \cdot \frac{c \log n}{24}$ for all x and y .

Can make this $1 - \frac{1}{\text{poly}(n)}$ with an arbitrarily large exponent by selecting c to be a sufficiently large constant.

This finishes the proof of correctness.

Summary

Main tool: Chernoff bound.

- $O(\log^2 n)$ subsets are needed because:
 - Need to try all $O(\log n)$ sampling probabilities: $1, \frac{1}{2}, \frac{1}{4}, \dots, \frac{1}{n}$.
 - For each of them, need to repeat for $O(\log n)$ times to get a “with high probability” guarantee.



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 - For each of them, need to repeat for $O(\log n)$ times to get a “with high probability” guarantee.

If we are happy with an “in expectation” guarantee, then this is not needed!

$$\mathbb{E}[\|f(x) - f(y)\|_1] \leq d(x, y) \in O(\log n) \cdot \mathbb{E}[\|f(x) - f(y)\|_1]$$

Outlook

- We have finished the proof for $O(\log n)$ -approximation of conductance.

This allows us to obtain a cut of conductance $O(\Phi(G) \cdot \log n)$ in polynomial time.

- **Next:** A completely different approach to conductance approximation via spectral graph theory.

This allows us to obtain a cut of conductance $O\left(\sqrt{\Phi(G)}\right)$ in polynomial time.



This is better whenever $\Phi(G) \in \omega(1/\log^2 n)$.

References

- **Main reference:**
 - Lecture 2.2 of <https://sites.google.com/site/th saranurak/teaching/Expander>
 - Chapter 11 of <https://lucatrevisan.github.io/books/expanders-2016.pdf>