President's Day Lecture:

Advanced Nearest Neighbor Search

[Advanced Algorithms, Spring'17]

Announcements

- Evaluation on CourseWorks
- If you think homework is too easy (or too hard):
  - mark "appropriateness of workload"

Time-Space Trade-offs (Euclidean)

space	query time	Space	Time	Comment	Reference
low	high	$\approx n$	n^{σ}	$\sigma = 2.09/c$	[Ind'01, Pan'06]
				$\sigma = O(1/c^2)$	[AI'06]
medium	medium	$n^{1+\rho}$	n^{ρ}	$\rho = 1/c$	[IM'98, DIIM'04]
				$\rho = 1/c^2$	[AI'06]
				$\rho \geq 1/c^2$	[MNP'06, OWZ'11]
		$n^{1+o(1/c^2)}$	ω(1) memory lookups		[PTW'08, PTW'10]
high	low	n^{4/ϵ^2}	$\cancel{O(d \log n)}$ 1 mem lookup	$c = 1 + \epsilon$	[KOR'98, IM'98, Pan'06]
		$n^{o(1/\epsilon^2)}$	ω(1) memory lookups		[AIP'06]

Near-linear Space for $\{0,1\}^d$

[Indyk'01, Panigrahy'06]

Sample a few buckets in the same hash table!

- Setting:
  - Close: $r = \frac{d}{2c} \Rightarrow P_1 = 1 - \frac{1}{2c}$
  - Far: $cr = \frac{d}{2} \Rightarrow P_2 = \frac{1}{2}$
- Algorithm:
  - Use one hash table with $k = \frac{\log n}{\log 1/P_2} = \alpha \cdot \ln n$
  - On query q:
    - compute $w = g(q) \in \{0,1\}^k$
    - Repeat $R = n^\sigma$ times:
      - w': flip each w_j with probability $1 - P_1$
      - look up bucket w' and compute distance to all points there
    - If found an approximate near neighbor, stop

Near-linear Space

- Theorem: for $\sigma = \Theta\left(\frac{\log c}{c}\right)$, we have:
  - Pr[find an approx near neighbor]≥ 0.1
  - Expected runtime: $O(n^{\sigma})$
- Proof:
  - Let p^* be the near neighbor: $||q - p^*|| \leq r$
  - $w = g(q), t = ||w - g(p^*)||_1$
  - Claim 1: $\Pr_g\left[t \leq \frac{k}{c}\right] \geq \frac{1}{2}$
  - Claim 2: $\Pr_{g,w'}\left[w' = g(p) \mid ||q - p||_1 \geq \frac{d}{2}\right] \leq \frac{1}{n}$
  - Claim 3: $\Pr[w' = g(p^*) \mid Claim\ 1] \geq 2n^{-\sigma}$
  - If $w' = g(p^*)$ at least for one w', we are guaranteed to output either p^* or an approx. near neighbor

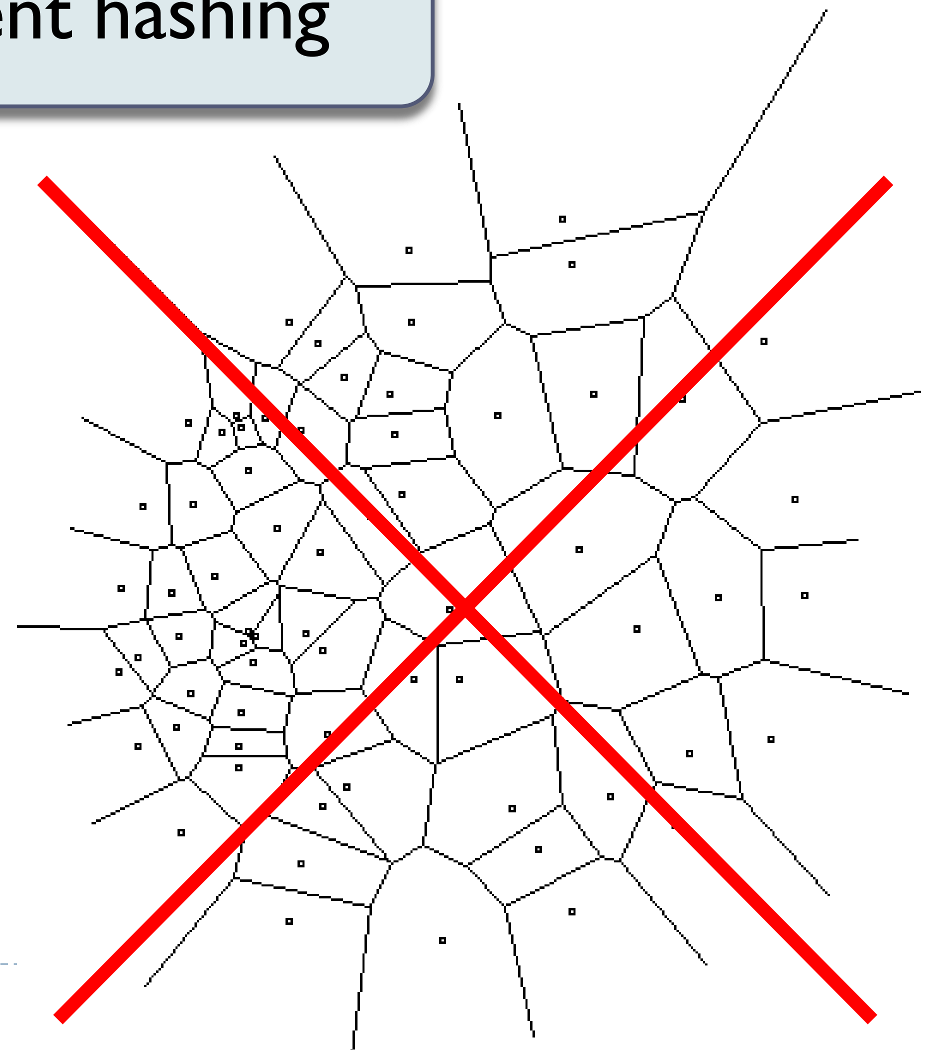
Beyond LSH

	Space	Time	Exponent	$c = 2$	Reference	
Hamming space	$n^{1+\rho}$	n^{ρ}	$\rho = 1/c$	$\rho = \mathbf{1/2}$	[IM'98]	LSH
			$\rho \geq 1/c$		[MNP'06, OWZ'11]	LSH
	$n^{1+\rho}$	n^{ρ}	$\rho \approx \frac{1}{2c-1}$	$\rho = \mathbf{1/3}$	[AINR'14, AR'15]	
Euclidean space	$n^{1+\rho}$	n^{ρ}	$\rho \approx 1/c^2$	$\rho = \mathbf{1/4}$	[AI'06]	LSH
			$\rho \geq 1/c^2$		[MNP'06, OWZ'11]	LSH
	$n^{1+\rho}$	n^{ρ}	$\rho \approx \frac{1}{2c^2-1}$	$\rho = \mathbf{1/7}$	[AINR'14, AR'15]	

New approach?

Data-dependent hashing

- A random hash function, chosen after seeing the given dataset
- Efficiently computable



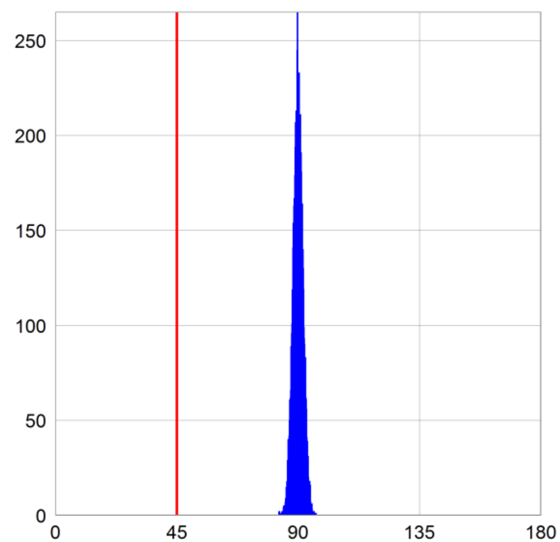
Construction of hash function

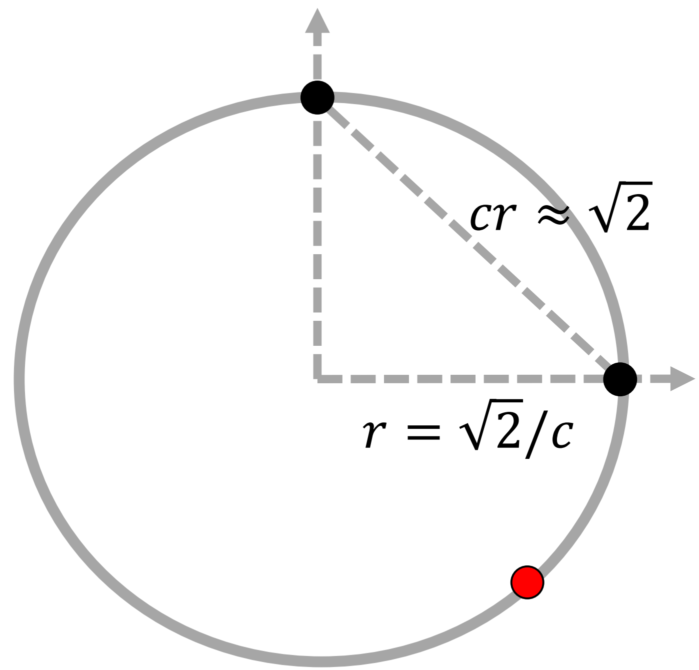
[A.-Indyk-Nguyen-Razenshteyn'14, A.-Razenshteyn'15]

- Two components:
  - Nice geometric structure ⟸ has better LSH
  - Reduction to such structure ⟸ data-dependent

Nice geometric structure

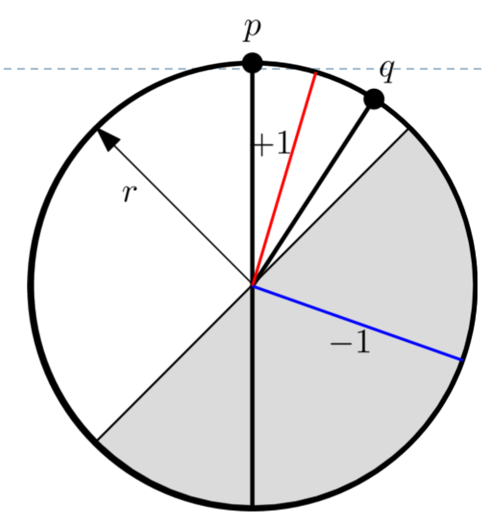
- Points on a unit sphere, where
  - $cr \approx \sqrt{2}$, i.e., far pair is (near) orthogonal
  - this would be distance if the dataset were random on sphere
  - Close pair: $r = \sqrt{2}/c$
- Query:
  - at angle 45' from near-neighbor



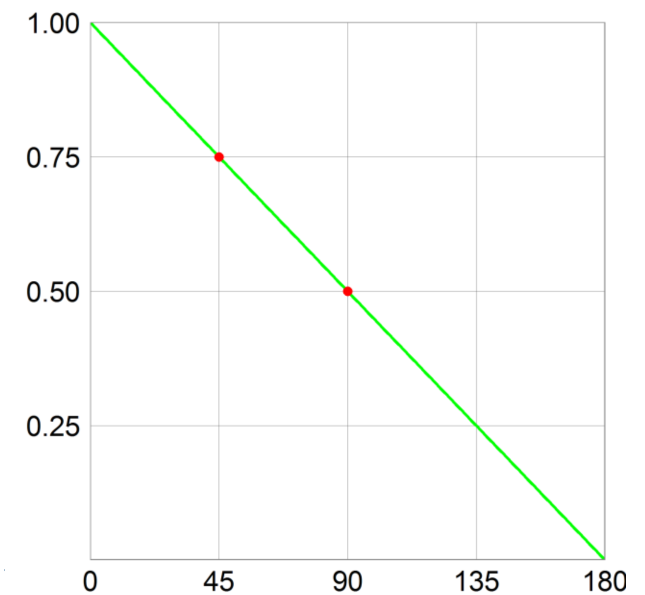


Alg 1: Hyperplanes

[Charikar'02]



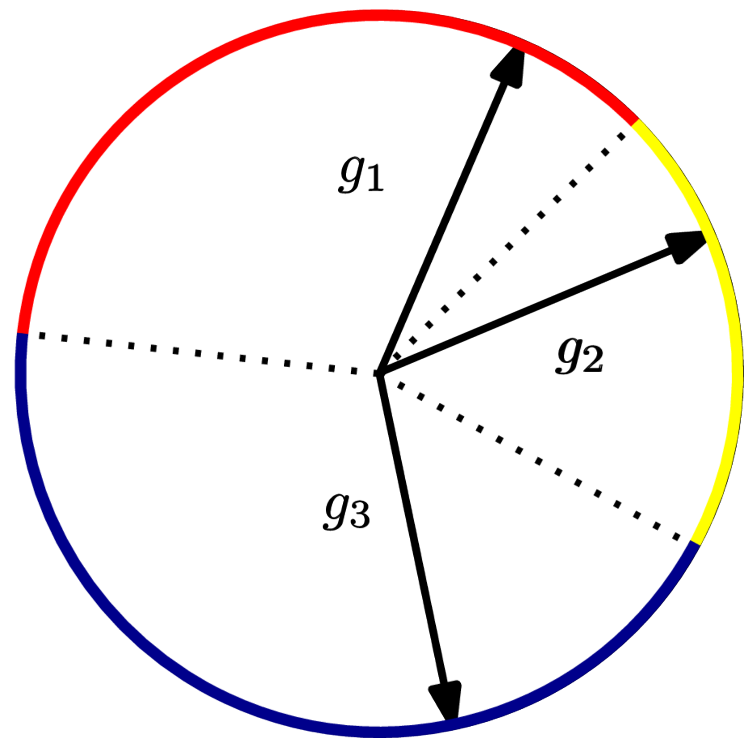
- Sample *unit* r uniformly, hash p into $sgn\langle r, p\rangle$
  - $\Pr[h(p) = h(q)]$?
    $= 1 - \alpha / \pi$
  - where α is the angle between p and q
- $P_1 = 3/4$
- $P_2 = 1/2$
- $\rho \approx 0.42$



Alg 2: Voronoi

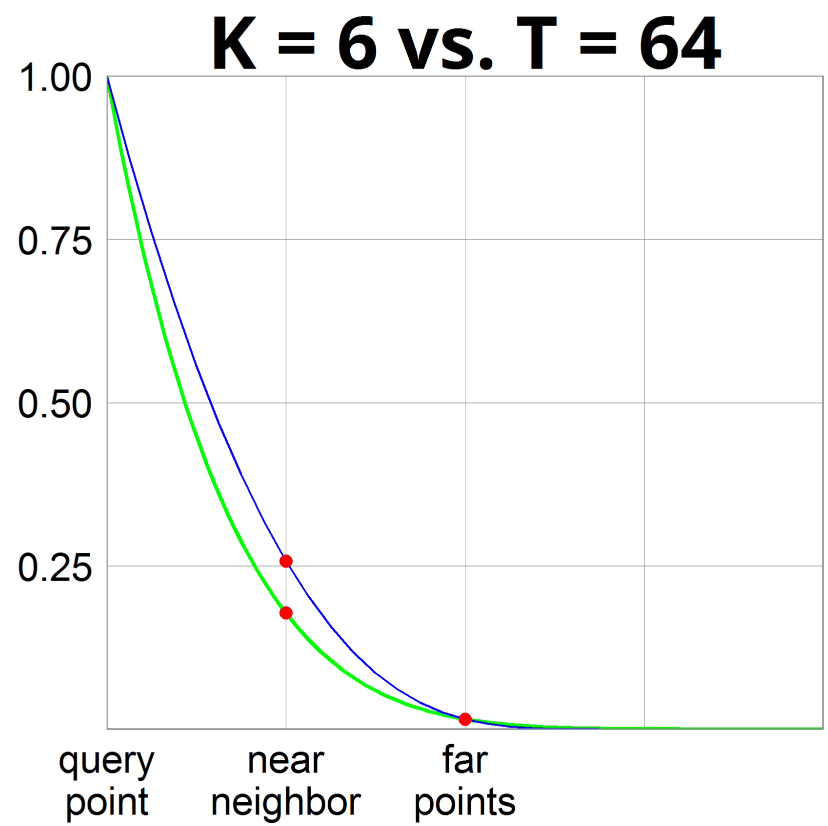
[A.-Indyk-Nguyen-Razenshteyn'14] based on [Karger-Motwani-Sudan'94]

- Sample T i.i.d. standard d-dimensional Gaussians
$$g_1, g_2, \ldots, g_T$$
- Hash p into
$$h(p) = \ argmax_{1 \le i \le T} \langle p, g_i \rangle$$
- $T = 2$ is simply Hyperplane LSH



Hyperplane vs Voronoi

- Hyperplane with $k = 6$ hyperplanes
  - Means we partition space into $2^6 = 64$ pieces
- Voronoi with $T = 2^k = 64$ vectors
  - $\rho = 0.18$
  - grids vs spheres

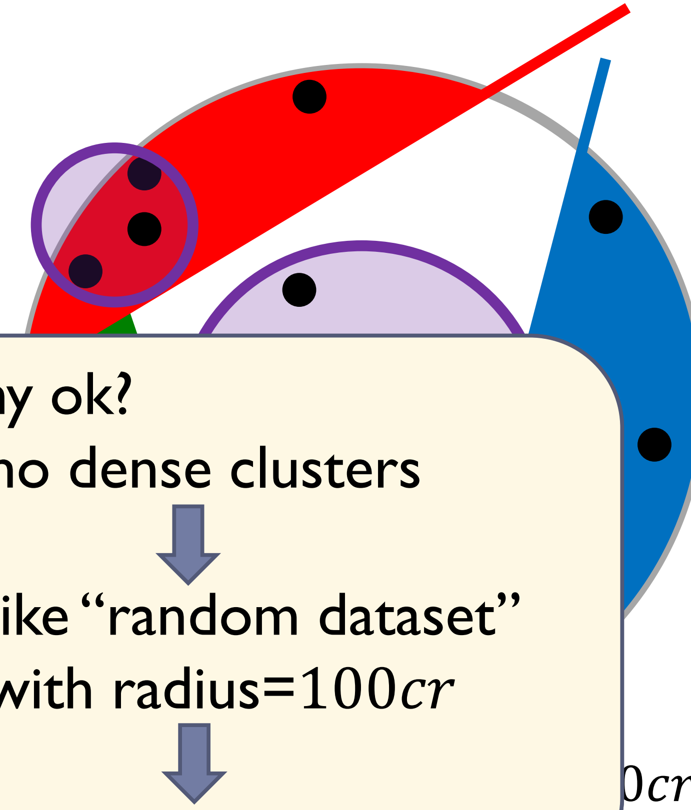


Reduction to nice structure (very HL)

- Idea:

  iteratively decrease the radius of minimum enclosing ball OR make more isotopic

- Algorithm:
  - find dense clusters
    - with smaller radius
    - large fraction of points
  - recurse on dense clusters
  - apply VoronoiLSH on the rest
    - recurse on each "cap"
    - eg, dense clusters might reappear



Why ok?

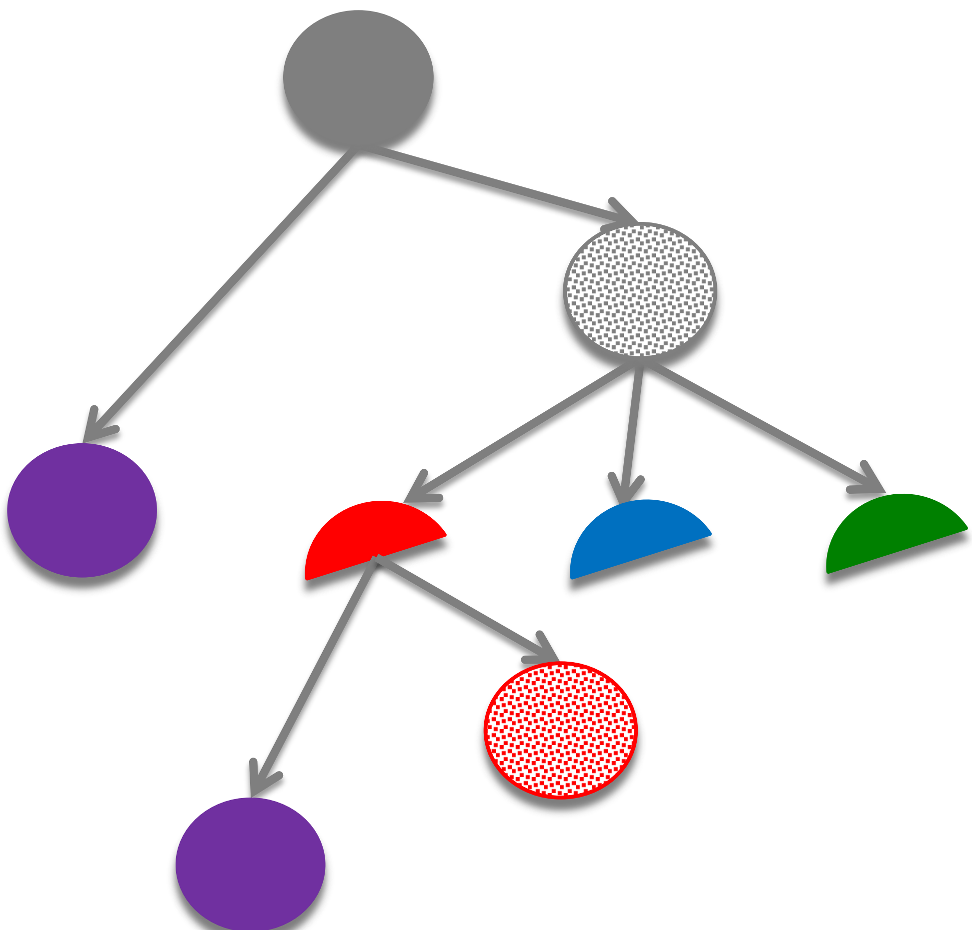
- no dense clusters
- like "random dataset" with radius=$100cr$
- even better!

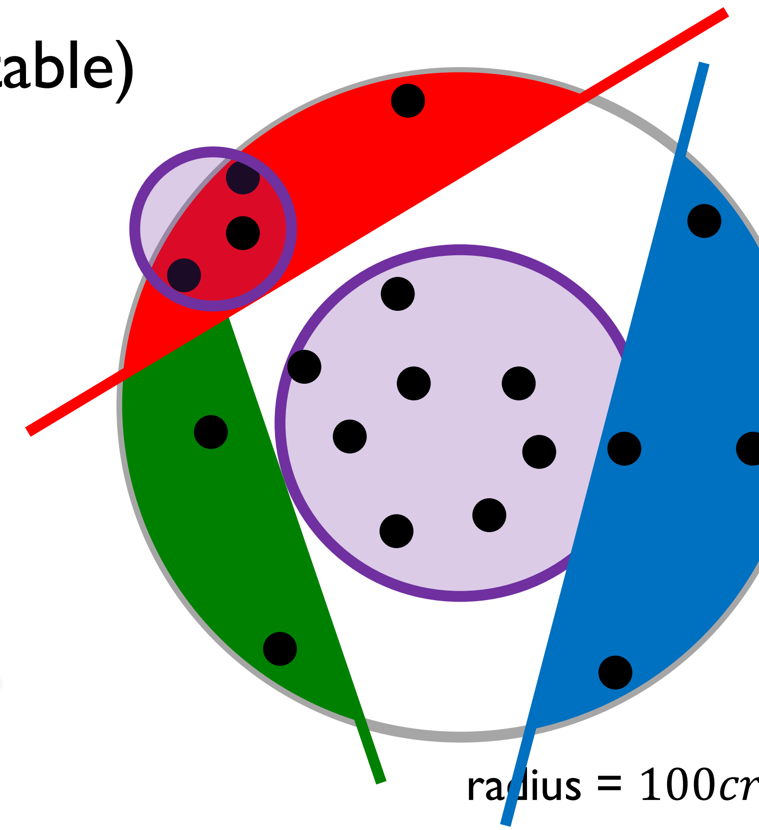
radius = $99cr$

*picture not to scale & dimension

Hash function

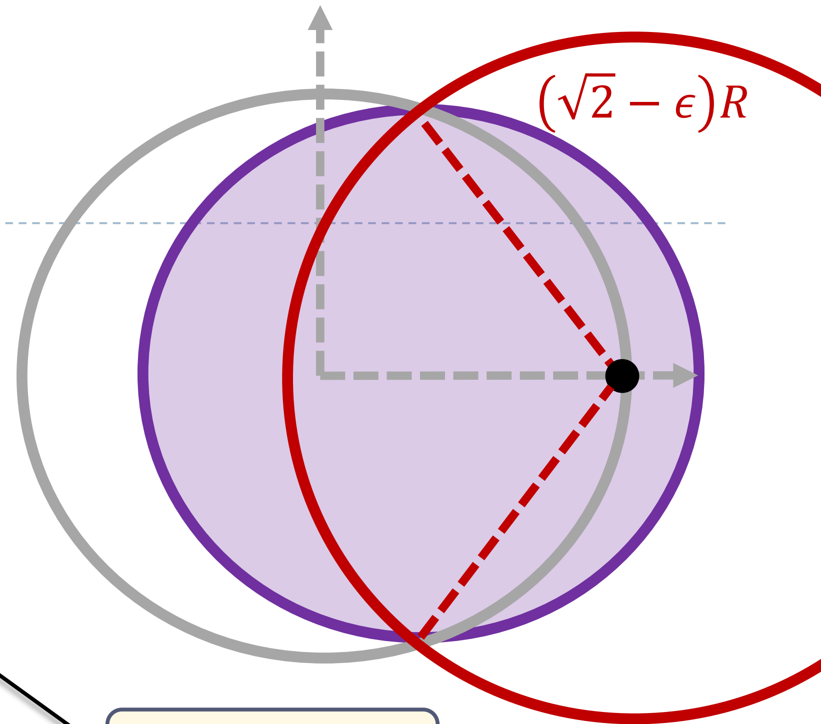
- Described by a tree (like a hash table)





*picture not to scale&dimension

Dense clusters



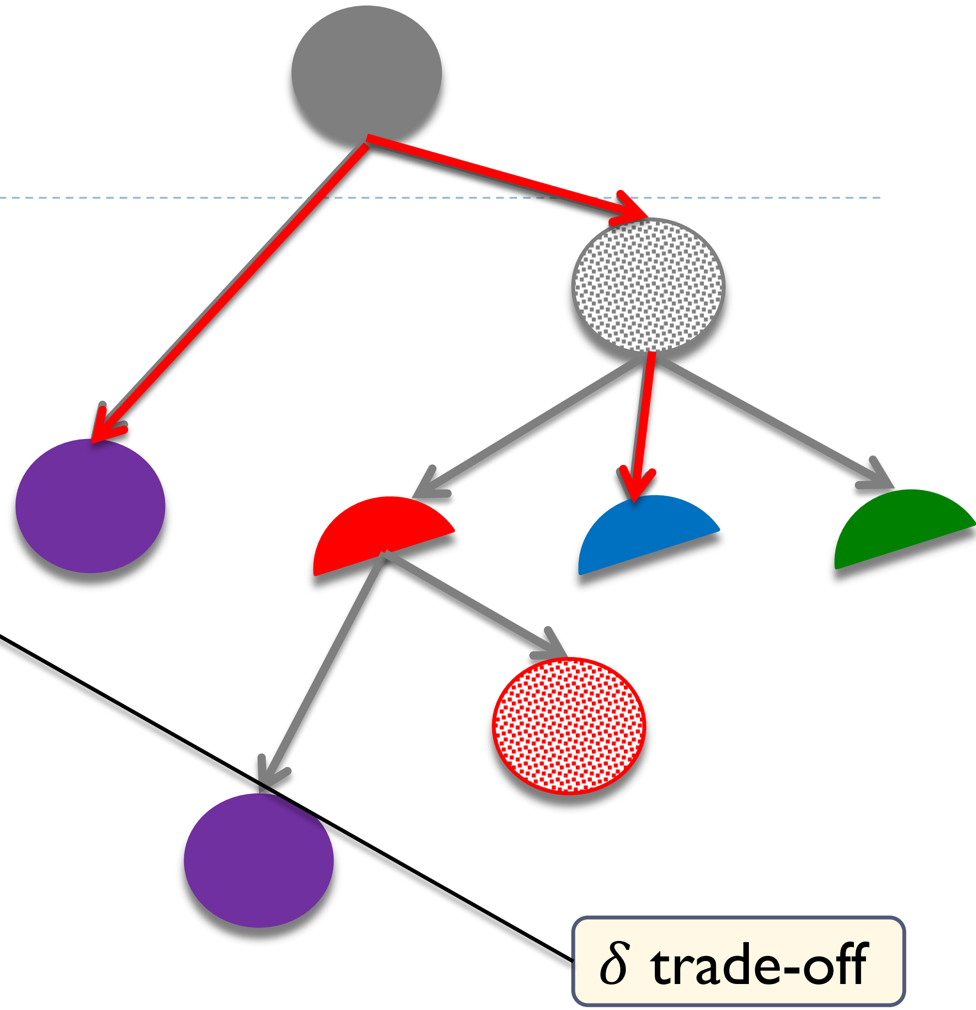
- Current dataset: radius R
- A dense cluster:
  - Contains $n^{1-\delta}$ points
  - Smaller radius: $(1-\Omega(\epsilon^2))R$
- After we remove all clusters:
  - For any point on the surface, there are ϵ trade-off points within distance $(\sqrt{2}-\epsilon)R$
  - The other points are essentially orthogonal !
- When applying Cap Carving with parameters (P_1, P_2):
  - Empirical number of far pts colliding with query: $nP_2 + n^{1-\delta}$
  - As long as $nP_2 \gg n^{1-\delta}$, the "impurity" doesn't matter!

δ trade-off

?

Tree recap

- During query:
  - Recurse in all clusters
  - Just in one bucket in VoronoiLSH
- Will look in >1 leaf!
- How much branching?
  - Claim: at most $\left(n^{\delta}+1\right)^{O(1/\epsilon^2)}$
  - Each time we branch
    - at most n^{δ} clusters $(+1)$
    - a cluster reduces radius by $\Omega(\epsilon^2)$
    - cluster-depth at most $100/\Omega(\epsilon^2)$
- Progress in 2 ways:
  - Clusters reduce radius
  - CapCarving nodes reduce the # of far points (empirical P_2)
- A tree succeeds with probability $\geq n^{-\frac{1}{2c^2-1}-o(1)}$



NNS: conclusion

- 1. Via sketches
- 2. Locality Sensitive Hashing
  - Random space partitions
  - Better space bound
    - Even near-linear!
- 3. Data-dependent hashing even better
    - Used in practice a lot these days