

Reconstructing Riemannian Metrics From Random Geometric Graphs

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Abstract

Random geometric graphs are random graph models defined on metric measure spaces. A random geometric graph is generated by first sampling points from a metric space and then connecting each pair of sampled points independently with a probability that depends on their distance.

In recent work of Huang, Jiradilok, and Mossel [Huang et al. \(2024\)](#), the authors study the problem of reconstructing an embedded manifold from a random geometric graph sampled from the manifold, where edge probabilities depend monotonically on the Euclidean distance between the embedded points. They show that, under mild regularity assumptions on the manifold, the sampling measure, and the connection probability function, it is possible to recover the pairwise Euclidean distances of the embedded sampled points up to a vanishing error as the number of vertices grows.

In this work we consider a similar and arguably more natural problem where the metric is the Riemannian metric on the manifold. Again points are sampled from the manifold and a random graph is generated where the connection probability is monotone in the Riemannian distance. Perhaps surprisingly we obtain stronger results in this setup. Unlike the previous work that only considered dense graph we provide reconstruction algorithms from sparse graphs with average degree $n^{1/2}\text{polylog}(n)$, where n denotes the number of vertices. Our algorithm is also a more efficient algorithm for distance reconstruction with improved error bounds. The local distance-estimation part runs in $O(n^2 \text{polylog}(n))$ time, and the final all-pairs shortest-path step gives an overall running time of $O(n^3)$. Our distance error also nearly matches the volumetric lower bounds for distance estimation.

1. Introduction

Random graphs provide a powerful framework for modeling complex networks. The classical Erdős–Rényi model $G(n, p)$, in which edges appear independently with probability p , remains a cornerstone of modern probabilistic combinatorics, offering analytic clarity for studying connectivity, typical distances, and phase transitions. Comprehensive references include [Bollobás \(2011\)](#); [Janson et al. \(2011\)](#) and the survey [Frieze and Karoński \(2015\)](#).

To model more complex and realistic graphs it is natural to consider edge probabilities that depend on spatial or geometric proximity. Random geometric graphs (RGGs) model this phenomenon by associating latent positions to vertices and defining adjacency as a function of distance. In the classical hard-disc model, two vertices v, w are connected whenever

the latent positions X_v, X_w satisfy $\text{dist}(X_v, X_w) \leq r$. The soft or random-connection model generalizes this by assigning connection probabilities $p(\text{dist}(X_v, X_w))$ that decay with distance, reflecting fading or noisy interactions as observed for example in wireless and spatial networks [Penrose \(2003\)](#); [Dettmann and Georgiou \(2016\)](#).

An exciting new research direction in the study of RGGs concerns the extent to which one can infer latent geometric or probabilistic structure from the observed connectivity pattern. Earlier work established detectability thresholds distinguishing geometric graphs from Erdős–Rényi graphs in various regimes [Bubeck et al. \(2016\)](#); [Liu et al. \(2022\)](#); [Brennan et al. \(2020\)](#). Other studies have explored nonparametric inference for translation-invariant RGGs on spheres, aiming to recover the connection kernel $p(\langle x, y \rangle)$ from a single graph [Araya and De Castro \(2019\)](#); [Eldan et al. \(2022\)](#); [Duchemin and De Castro \(2023\)](#).

A recent work of Huang, Jiradilok, and Mossel [Huang et al. \(2024\)](#) initiated the study of *distance reconstruction* from a single random geometric graph sampled on a manifold. Conceptually, this frames a geometric inverse problem: *to what extent can the metric structure of a continuous space be recovered from a single noisy combinatorial observation?* They addressed this problem under a relatively mild set of assumptions: In their model, one observes a graph generated from i.i.d. samples $X_1, \dots, X_n \sim \mu$ on a smooth, compact, connected d -dimensional submanifold $M \subset \mathbb{R}^N$ (without boundary), where each edge $\{i, j\}$ is included independently with probability $p(\|X_i - X_j\|)$, with p non-increasing and bi-Lipschitz on $[0, \text{diam}(M)]$, and μ satisfying a lower Ahlfors regularity condition (see Assumption 1.3). Assuming additionally that p , d , curvature bounds, and a quantitative non-self-intersection bound are provided, they give an $O(n^3)$ -time algorithm that reconstructs all pairwise ambient Euclidean distances (up to vanishing error) with high probability.

1.1. Our Contributions and comparison to prior work.

In this paper, we consider a different natural variant of the question studied in [Huang et al. \(2024\)](#). Here, we consider the case where the latent space is a compact Riemannian manifold (M, g) without boundary, equipped with a probability measure μ satisfying lower Ahlfors regularity as above. Crucially the probabilities of edges are now determined by a connection probability function p applied to the intrinsic distance between the points on the manifold. This is arguably a better model, as for example, on Earth it is more natural to measure distances by the distance needed to travel rather than by the Euclidean distance in 3 dimensions. Our results also relax the condition on the connection function p to be Lipschitz continuous, but only bi-Lipschitz on a small interval $[0, r_p]$ near zero (see Definition 1.2). We introduce a *sparsity parameter* $s_n \in (0, 1]$ into the model, allowing each edge to appear independently with probability $s_n p(|X_i X_j|)$, where

$$|X_i X_j| := \text{the Riemannian distance between } X_i \text{ and } X_j \text{ on } M.$$

Informally, our main theorem is stated below; see Theorem 1.6 for a formal statement.

Theorem A *[Informal] There exists an $O(n^3)$ -time algorithm that, given a random geometric graph $G \sim G(n, M, g, \mu, p, s_n)$, with sparsity parameter*

$$1 \geq s_n = \omega\left(\frac{\log n}{\sqrt{n}}\right),$$

p , and some bounds on the geometric properties of (M, g) , the regularity of μ , produces an estimator of all pairwise distances. With high probability, all vertex pairs v, w ,

$$|d(v, w) - |X_v X_w|| \leq C \left(\frac{\log^2 n}{s_n n} \right)^{\frac{1}{d+2}},$$

where C is a constant depending only on geometric properties of M (sectional curvature bounds, injectivity radius, diameter), the regularity parameters of μ , and the bi-Lipschitz properties of p .

To further complement our result, we also establish a lower bound showing that no algorithm can achieve a uniform distance error of order smaller than $n^{-4/d} / \log n$ with high probability; see Theorem 1.7 below. Also as a benchmark, if one wants to cover a d -dimensional manifold with a $n^{-1/d}$ -net, then one needs about n points. Thus, our upper bound is getting close to the natural volumetric scale for distance resolution.

Comparison to prior work Huang et al. (2024). A direct comparison to the previous work Huang et al. (2024) is summarized in the following table.

	metric	regime	time	uniform error
Huang et al. (2024)	ambient Euclidean	dense	$O(n^3)$	$n^{-\varepsilon/d}$
this work	geodesic	$s_n = \omega\left(\frac{\log n}{\sqrt{n}}\right)$	$O(n^3)$	$(\log^2 n / (s_n n))^{1/(d+2)}$

We also remark that our main result only assumes that p is bi-Lipschitz on $[0, r_p]$, so for distances beyond this range we globalize local estimates via a shortest-path computation, which has running time $O(n^3)$. If, in addition, p is bi-Lipschitz on $[0, \text{diam}(M)]$ (as in Huang et al. (2024)), then the final shortest-path step can be omitted; in this case the overall running time drops to $O(n^2 \text{polylog} n)$, a reduction from $O(n^3)$ comparing to Huang et al. (2024).

Relation to manifold learning. The goal of *manifold learning* is to infer *low-dimensional geometric structure* from data sampled on (or near) an unknown manifold, see e.g. Duchemin and De Castro (2023); Araya and De Castro (2019); Fefferman et al. (2021, 2020b, 2023); Atamanchuk et al. (2023) among many others. Our setting differs in a key way: we do not observe the ambient coordinates or pairwise Euclidean distances, and the neighborhood graph itself is a *single unweighted random graph* whose edges appear with probabilities depending on intrinsic distances. Thus, our problem can be viewed as manifold learning from *connectivity alone*, where the main goal is explicit reconstruction of intrinsic distances (and the induced metric-measure structure), rather than producing a low-dimensional embedding. Indeed, by feeding the output of our algorithm into the framework Fefferman et al. (2020a, 2021), one can construct a Riemannian manifold that is close to the one from which the data were sampled. Another line of research related to manifold learning is due to Aizenbud and Sober (2025, 2021), who consider noisy observations in a tubular neighborhood of a smooth manifold and develop methods that, for a given query point, estimate its projection onto the manifold together with the local tangent space, with provable consistency and rates.

1.2. Formal Definitions and Statements

We now present the formal definitions, standing assumptions, and the main results.

Assumption 1.1 (Manifold) *We assume that (M, g) is a compact, connected, smooth Riemannian manifold of dimension $d \geq 2$. Let $K(\sigma)$ denote the sectional curvature at a 2-plane $\sigma \subset TM$, and define*

$$\kappa := \sup_{\sigma} |K(\sigma)|,$$

which is finite by compactness of M . Let $r_{\text{inj}}(M)$ denote the injectivity radius of M , which is also positive due to compactness.

Assumption 1.2 (Distance–probability function) *Let $p : [0, \infty) \rightarrow [0, 1]$ be a non-increasing function. We assume there exist positive constants $L_p, \ell_p, r_p > 0$ such that*

- *for all $a, b \in [0, r_p]$, $|p(a) - p(b)| \geq \ell_p |a - b|$, and*
- *for all $a, b \in [0, \text{diam}(M)]$, $|p(a) - p(b)| \leq L_p |a - b|$.*

That is, p is bi-Lipschitz on $[0, r_p]$ and globally Lipschitz on $[0, \text{diam}(M)]$. We refer to p as the distance–probability function.

Assumption 1.3 (Sampling measure) *Let μ be a probability measure on M , and define*

$$\mu_{\min}(r) := \min_{p \in M} \mu(B_r(p)).$$

We assume that μ satisfies a lower Ahlfors regularity condition: there exist constants $r_\mu > 0$ and $c_\mu > 0$ such that

$$\mu_{\min}(r) \geq c_\mu r^d, \quad \forall r \in [0, r_\mu]. \quad (1)$$

Definition 1.4 (Random geometric graph) *Given a triple (M, μ, p) , a vertex set $\mathbf{V}$ with $|\mathbf{V}| = n$, and a sparsity parameter $s_n \in (0, 1]$, define the random geometric graph $G(\mathbf{V}, M, g, \mu, p, s_n)$ as follows. Sample i.i.d. points $\{X_v\}_{v \in \mathbf{V}}$ from μ , and let $\{\mathcal{U}_{i,j}\}_{i \neq j}$ be i.i.d. $\text{Uniform}(0, 1)$ random variables. The edge set of G is*

$$E(G) = \left\{ \{i, j\} \in \binom{\mathbf{V}}{2} : \mathcal{U}_{i,j} < s_n p(|X_i - X_j|) \right\}.$$

For brevity we write $G(n, M, g, \mu, p, s_n)$ when $|\mathbf{V}| = n$.

Definition 1.5 (Accessible radius) *Define*

$$r_G := \frac{1}{16} \min \left\{ r_p, r_{\text{inj}}(M), \frac{1}{\sqrt{\kappa}}, r_\mu \right\}.$$

This constant depends only on (M, g) , p , and μ . Within distance r_G , the manifold is approximately Euclidean, μ satisfies lower Ahlfors regularity, and p behaves bi-Lipschitzly.

Theorem 1.6 Assume $s_n^2 n = \omega(\log^2 n)$. There exists an algorithm (Algorithm 5) running in time $O(n^3)$ such that the following holds.

For any (M, g, μ) satisfying Assumptions 1.1 and 1.3, and any distance-probability function p satisfying Assumption 1.2, the algorithm takes as input

$$G \sim G(\mathbf{V}, M, g, \mu, p, s_n), \quad p, \quad s_n, \quad \text{a lower bound on both } r_G \quad \text{and } c_\mu,$$

and with probability $1 - n^{-\omega(1)}$ it outputs estimates $d(w, v)$ for all $w, v \in \mathbf{V}$ satisfying

$$|X_w X_v - d(w, v)| \leq C \left(\frac{\log^2 n}{s_n n} \right)^{1/(d+2)},$$

for all $w, v \in \mathbf{V}$, where C depends only on $d, L_p, \ell_p, c_\mu, r_G$, and $\text{diam}(M)$.

Theorem 1.7 (Lower bound) For every n , there exist two d -dimensional Riemannian manifolds (M_1, g_1, μ_1) and (M_2, g_2, μ_2) together with distance-probability functions p so that the following holds. First, the corresponding r_G and c_μ are bounded below, and the diameters are bounded above, by positive constants independent of n . Second, there exists a coupling π of the random geometric graphs

$$G(n, M_1, g_1, \mu_1, p, 1) \quad \text{and} \quad G(n, M_2, g_2, \mu_2, p, 1),$$

such that with probability $1 - o_n(1)$ for $(G_1, G_2) \sim \pi$, we have $G_1 = G_2$ and

$$|X_u^{(1)} X_v^{(1)}|_{M_1} - |X_u^{(2)} X_v^{(2)}|_{M_2}| \geq c \frac{n^{-4/d}}{\log n}$$

for some $\{u, v\} \subseteq V(G_1) = V(G_2)$. Here $X_u^{(i)}$ denotes the latent point in M_i corresponding to vertex u in G_i , and $c > 0$ depends only on the dimension d and the curvature bound κ .

1.3. Ideas from the Proof

We sketch some of the main ideas of the proof. For the discussion below, we assume that $\mathbf{V}$ denotes the vertex set of the graph. We begin by outlining the main ideas and the overall construction of the algorithm, illustrating the comparison from the approach in Huang et al. (2024). The emphasis in this first part is on the algorithmic aspects and we treat the embedded manifold and the Riemannian manifold settings uniformly by subsuming both under the umbrella term “locally Euclidean.” In the second part, we turn to the geometric aspects and discuss how to extend the approach to the Riemannian manifold setting.

1.3.1. CLUSTERS AND CLUSTER EDGE DENSITY

Cluster edge density approach. A natural idea that was already used in Huang et al. (2024) is that *given* a cluster of nearby points, we can use concentration to estimate the distance from (points in) this cluster to a point that is far away. We first elaborate on this idea and will then discuss how to find clusters.

For any vertex v and a small parameter ξ , suppose we are given the vertex subset U_v such that, for every $v' \in U_v$,

$$|X_v X_{v'}| \leq \xi.$$

Then, for any other vertex w , we estimate $|X_v X_w|$ by the edge density from U_v to w , as follows.



Figure 1: For $|X_v X_w|$ in the bi-Lipschitz regime of p , edge density from cluster U_v to vertex w reveals $p(|X_v X_w|)$.

First, for any $v' \in U_v$, since $|X_v X_{v'}| \leq \xi$, the Lipschitz continuity of p implies

$$|p(|X_v X_w|) - p(|X_{v'} X_w|)| \leq L_p \xi.$$

Second, conditional on the latent locations $X_{U_v} = \{X_{v'}\}_{v' \in U_v}$ and X_w , the edges between U_v and w appear independently with probability $s_n p(|X_{v'} X_w|)$. Hence the number of such edges is a sum of independent Bernoulli random variables with mean

$$s_n \sum_{v' \in U_v} p(|X_{v'} X_w|).$$

By a Chernoff bound, with probability at least $1 - n^{-\omega(1)}$,

$$\left| (\# \text{ of edges from } U_v \text{ to } w) - s_n \sum_{v' \in U_v} p(|X_{v'} X_w|) \right| \leq O(\sqrt{s_n |U_v| \log n}).$$

Normalizing by $s_n |U_v|$ yields the estimator

$$p(|X_v X_w|) = \mathbf{N}_{U_v}(w) + O(\xi + \varepsilon_{U_v}),$$

where

$$\mathbf{N}_{U_v}(w) := \frac{\# \text{ of edges from } U_v \text{ to } w}{s_n |U_v|} \quad \text{and} \quad \varepsilon_{U_v} := \sqrt{\frac{\log n}{s_n |U_v|}}.$$

If $|X_v X_w|$ is in the bi-Lipschitz regime of p , then we can invert p to estimate $|X_v X_w|$ up to error $O(\xi + \varepsilon_{U_v})$. Thus, the error in estimating $|X_v X_w|$ has two components: the *fluctuation error* ε_{U_v} from edge randomness, and the *radius error* ξ from replacing $p(|X_{v'} X_w|)$ by $p(|X_v X_w|)$ for $v' \in U_v$.

Balancing the two errors. Suppose ξ is small relative to r_G defined in (1.5), and take the “optimal” set

$$U_v := \{v' \neq v : |X_v X_{v'}| \leq \xi\}.$$

If μ is the uniform measure on M , then

$$|U_v| = \frac{\text{Vol}(B_\xi(X_v))}{\text{Vol}(M)} n \gtrsim \xi^d n.$$

For X_v and X_w not too far apart (in the Bi-Lipschitz regime of p), we have

$$s_n \sum_{v' \in U_v} p(|X_{v'} X_w|) \simeq s_n |U_v|,$$

so the fluctuation scale is $\sqrt{s_n |U_v|} \simeq \sqrt{s_n \xi^d n}$. Balancing the two errors gives

$$\xi \simeq (s_n n)^{-\frac{1}{d+2}}.$$

Consequently, this cluster edge density method estimates $p(|X_v X_w|)$ up to error $(s_n n)^{-\frac{1}{d+2}}$, which is the rate achieved in Theorem 1.6. In other words, if for each vertex v we can find a set U_v of size at least $\xi^d n$ within radius ξ , with the choice of ξ above, then we can estimate all pairwise distances up to error $O((s_n n)^{-\frac{1}{d+2}})$. For vertices v, w that are far apart, we can rely on the fact that the geodesic distance is a path metric, meaning that we can estimate $|X_v X_w|$ by summing up the estimated distances along a path of short hops between v and w .

1.3.2. FINDING CLUSTERS VIA COMMON-NEIGHBOR COUNTS IN [HUANG ET AL. \(2024\)](#)

For a subset W of vertices, call it (ε, m) -dense if, for every $i \in W$, the set

$$W_i := \{i' \in W : |X_i X_{i'}| \leq \varepsilon\}$$

has size at least m .

Consider the feature map

$$i \in W \mapsto p_i : M \rightarrow [0, 1], \quad p_i(x) := p(|X_i x|),$$

and define the inner product

$$\langle p_i, p_j \rangle_W := \mathbb{E}_{Z \sim \mu} [p_i(Z) p_j(Z)].$$

Let $V_{\text{cn}} \subset V$ be another subset of vertices disjoint from W . For distinct $i, j \in W$, the number of common neighbors of i and j in V_{cn} is a sum of $|V_{\text{cn}}|$ independent Bernoulli random variables with mean $s_n^2 \langle p_i, p_j \rangle_W$, conditional on X_i, X_j . Thus we estimate $\langle p_i, p_j \rangle_W$ via the normalized common-neighbor count

$$N_{V_{\text{cn}}}(i, j) := \frac{\# \text{ of common neighbors between } i \text{ and } j}{s_n^2 |V_{\text{cn}}|},$$

except that the self inner product $\langle p_i, p_i \rangle_W$ is not directly observable.

The maximizer of $\langle p_i, p_j \rangle_W$ over $i, j \in W$ occurs at $i = j$; this holds even without a manifold structure for M or regularity of μ . To conclude the converse implication

$$\langle p_i, p_j \rangle_W \text{ near its maximum} \Rightarrow |X_i X_j| \text{ is small,}$$

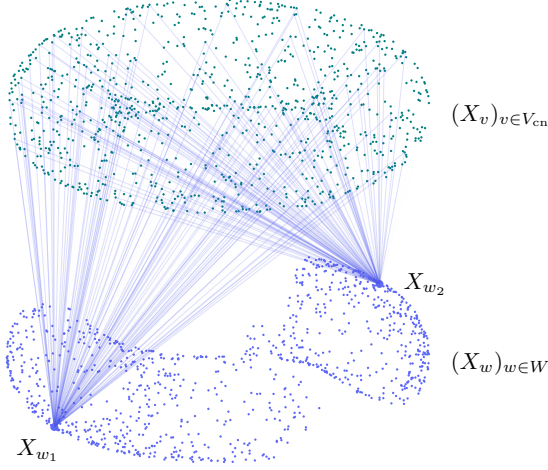


Figure 2: In the diagram, two set of latent points $X_W = (x_w)_{w \in W}$ and $X_{V_{cn}} = (x_v)_{v \in V_{cn}}$ are shown (with M being a torus). The (normalized) common neighbor count between any two vertices $w_1, w_2 \in W$ in V_{cn} estimates the inner product $\langle p_i, p_j \rangle_W$. When W is (ε, m) -dense with small ε , the closer the common neighbor count $N_{V_{cn}}(w_1, w_2)$ is to $\max_{w'_1, w'_2 \in \binom{W}{2}} N_{V_{cn}}(w'_1, w'_2)$, the smaller the latent distance $|X_{w_1} X_{w_2}|$ is.

we do rely heavily on the manifold structure of M , essentially that M is locally Euclidean, together with the lower Ahlfors d -regularity of μ . This idea goes back to [Huang et al. \(2024\)](#); here we adapt it to the Riemannian manifold setting. Building on it, we construct an algorithm (Algorithm 1) that, given any (ε, m) -dense set W with ε sufficiently small, extracts a cluster pair (U, u) with $u \in U \subseteq W$ such that

$$|U| \gtrsim m \quad \text{and} \quad |X_u X_{u'}| \leq O(\sqrt{\varepsilon}) \quad \text{for all } u' \in U, \quad (2)$$

by seeking (U, u) where each pair (u, u') has a common-neighbor count close to the maximum over all pairs in W . We remark that there is a loss in (2). When μ is uniform on M , the standard volumetric bound suggests any subset $W \subseteq \mathbf{V}$ can at most be $(\varepsilon, \Theta(\varepsilon^d n))$ -dense for $\varepsilon \gtrsim n^{-1/d}$. Thus the smallest non-empty cluster we can hope to extract from this approach has radius at least $\sqrt{n^{-1/d}} = n^{-1/(2d)}$, which is already suboptimal for the balanced choice of ξ in the cluster edge density method.

Iterative cluster extraction. The procedure above does not control which vertex is chosen as the cluster center u . To obtain clusters around different centers, we rerun the algorithm on suitably chosen subsets W that remain (ε, m) -dense.

Initialize with $W_1 = \mathbf{V}$ to obtain (U_1, u_1) . Suppose we have $(U_1, u_1), \dots, (U_k, u_k)$. Using the cluster edge density method, we can estimate the distances from every vertex to each $u_i, i \in [k]$. We then filter $\mathbf{V}$ to a smaller set W_{k+1} consisting of vertices that satisfy certain approximate distance constraints to the existing centers. If W_{k+1} is still (ε, m) -dense, we run the cluster extractor again to obtain a new cluster (U_{k+1}, u_{k+1}) whose center automatically satisfies the new constraints (since all vertices in W_{k+1} do). Iterating this yields enough clusters so that every $v \in \mathbf{V}$ is close to some cluster center u .

Orthogonal cluster frame. The main technical effort in [Huang et al. \(2024\)](#) is to prove that each filtered set W_{k+1} remains (ε, m) -dense, which requires careful control of error accumulation in the distance estimates. An intuitive visualization is that W_{k+1} typically corresponds to the intersection of several fuzzy annuli centered at the existing cluster centers $u_1, \dots, u_k$, where “fuzzy” reflects the uncertainty caused by estimation errors. The

“corners” and “boundaries” of this intersection are the regions most prone to losing density, making it challenging to ensure the (ε, m) -density property. A key intermediate step is that, for a given cluster (U_k, u_k) , one also extracts several *orthogonal clusters* around u_k , denoted $(U_{k,1}, u_{k,1}), \dots, (U_{k,d}, u_{k,d})$, such that the directions from X_{u_k} to $X_{u_{k,s}}$ for $s \in [d]$ are approximately orthogonal in the tangent space $T_{X_{u_k}} M$. With these $d + 1$ clusters, for any other vertex v whose latent position X_v is not too far from X_{u_k} , the distances $|X_v X_{u_{k,s}}|$ for $s \in [d]$ together with $|X_v X_{u_k}|$ — or, from observation of the graph, the edge densities from $U_{k,s}$ to v — can be interpreted as defining a local coordinate system around X_{u_k} . This local coordinate system helps control the geometry of the filtered set W_{k+1} (all vertices satisfying certain distance constraints to u_k and $u_{k,s}$ for $s \in [d]$), preserve its density, and enable the extraction of a new cluster near v in the next iteration, which is not too far from u_k in the latent distance.

Limitations in Huang et al. (2024). One of the main limitations of this approach is that the radius of each extracted cluster scales as $O(\sqrt{\varepsilon})$, rather than $O(\varepsilon)$, as mentioned in (2). From the earlier error-balancing analysis, this enlarged cluster radius leads to a suboptimal choice of ξ in the cluster edge density method.

Moreover, to preserve probabilistic independence during the iterative filtering and cluster extraction process, the method in Huang et al. (2024) partitions the vertex set into n^c disjoint subsets (for some constant $c > 0$), each of size n^{1-c} , and runs the cluster extraction algorithm on each subset whenever a new cluster is sought. This partitioning results in a degradation of the final error bound, since each subset contains only n^{1-c} vertices instead of the full n is weakening its (ε, m) -density property, which leads to a looser final error bound.

Finally, the dominant computational cost arises from computing the number of common neighbors for every pair of vertices in each working subset, which leads to an overall running time of $O(n^3)$.

1.3.3. OUR APPROACH

Our approach builds upon the framework of Huang et al. (2024), but stems from a simple yet powerful observation that was not use in Huang et al. (2024). Suppose we have a cluster (U, u) such that

$$|X_u X_{u'}| \leq \eta, \quad \forall u' \in U, \quad \text{and} \quad |U| \gtrsim \eta^d n,$$

for some radius parameter $\eta > 0$. Now consider two vertices v, w whose latent positions X_v, X_w are both not too far from X_u . Then the *difference* between the expected numbers of edges from U to v and from U to w is

$$\begin{aligned} & \mathbb{E}[\# \text{ of edges from } U \text{ to } v] - \mathbb{E}[\# \text{ of edges from } U \text{ to } w] \\ &= s_n \sum_{u' \in U} (p(|X_{u'} X_v|) - p(|X_{u'} X_w|)). \end{aligned}$$

By the Lipschitz continuity of p and the triangle inequality, we have

$$|p(|X_{u'} X_v|) - p(|X_{u'} X_w|)| = O(|X_v X_w|).$$

In fact, when X_v and X_w are relatively close but much farther from X_u than η , we can obtain a finer estimate:

$$c_\theta |X_v X_w| \leq (\mathbf{p}(|X_{u'} X_v|) - \mathbf{p}(|X_{u'} X_w|)) \leq C_\theta |X_v X_w|,$$

where θ denotes the angle $\angle X_u X_v X_w$ in the geodesic triangle formed by X_u, X_v, X_w centered at X_v , and $c_\theta, C_\theta > 0$ are constants depending on θ and $\mathbf{p}$. Consequently,

$$c_\theta |X_v X_w| - O(\varepsilon_U) \leq |N_{U_u} v - N_{U_u} w| \leq C_\theta |X_v X_w| + O(\varepsilon_U).$$

Importantly, unlike the cluster edge density distance estimator, this method introduces *no radius error*. In summary, while clusters with larger radii may be suboptimal for estimating the absolute distance $|X_u X_w|$ compared with the balanced-error cluster, they are significantly more effective at detecting *changes* in distance between two nearby points v and w . As an informal analogy, a coarse measurement scale may be unsuitable for measuring absolute lengths precisely, but can be more sensitive in detecting small relative changes.

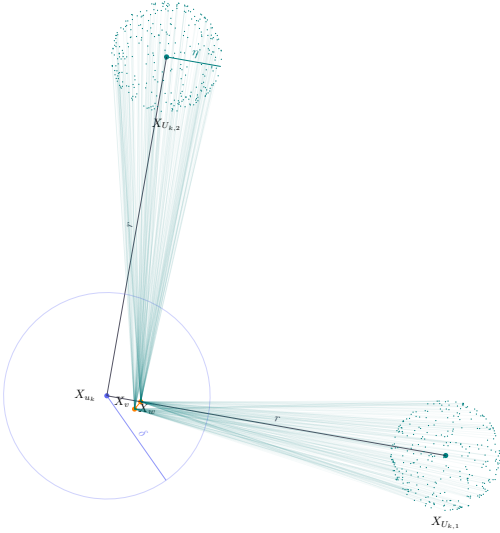


Figure 3: In the diagram, when two vertices v, w both lie within distance at most δ from the cluster center X_{u_k} —which can be estimated using the cluster edge density method—the difference in their common-neighbor counts $N_{U_{k,s}}(v)$ and $N_{U_{k,s}}(w)$, with respect to the orthogonal cluster $U_{k,s}$, provides an estimate of $|X_v X_w|$ up to a multiplicative error (through the mapping ϕ defined in (3)). This holds whenever $|X_v X_w| \gg \sqrt{\frac{\log n}{s_n n}}$, the dimension-free fluctuation scale. In particular, $|X_v X_w|$ can be negligible relative to the cluster radius η . (Here, $\eta < \delta < r < r_G$ are some parameters will be of order constants in the paper.)

Multiplicative error distance estimation down to dimension-free fluctuation. Suppose in addition we have found d clusters $(U_{u,s}, u_s)$, $s \in [d]$, around u , each satisfying the same size and radius conditions as (U, u) , and such that the directions from X_u to X_{u_s} for $s \in [d]$ are approximately orthogonal and have roughly equal lengths in the tangent space $T_{X_u} M$. Then, for any vertices v and w whose latent positions X_v, X_w are both not too far from X_u , define the vector

$$\phi := \left(\mathbf{p}^{-1}(N_{U_{u,s}} v) - \mathbf{p}^{-1}(N_{U_{u,s}} w) \right)_{s \in [d]}. \quad (3)$$

This vector serves as an approximate distance estimator satisfying

$$c |X_v X_w| - O(\varepsilon_U) \leq \|\phi\|_2 \leq C |X_v X_w| + O(\varepsilon_U),$$

for some constants $c, C > 0$. In this setting, it is advantageous to choose η to be a fixed constant fraction of the Accessible radius r_G defined in (1.5), which is independent of n . Then the fluctuation error satisfies

$$\varepsilon_U = O\left(\sqrt{\frac{\log n}{s_n n}}\right),$$

which is *dimension-free*. In other words, by leveraging differences in the common-neighbor counts across multiple clusters, as long as

$$\sqrt{\frac{\log n}{s_n n}} \ll |X_v X_w| \lesssim r_G,$$

we can estimate $|X_v X_w|$ up to a multiplicative error. Here, the upper bound ensures that all involved points remain within a locally Euclidean region of M , and the proper invertibility of p in this regime. Because the resulting error is multiplicative, this method outperforms the cluster edge density method whenever $|X_v X_w|$ is small comparing to $(\log n / (s_n n))^{1/(d+2)}$.

Two-stage approach. Our distance estimation algorithm (Algorithm 5) combines the two ideas above into a unified two-stage framework.

Stage 1: Cluster with constant radius construction. Following the general structure of Huang et al. (2024), we iteratively extract clusters (U_k, u_k) for $k = 1, 2, \dots$ until they form a δ -net of M , where δ is a small constant fraction of r_G . Around each center u_k , we further obtain d orthogonal clusters $(U_{k,s}, u_{k,s})$ for $s \in [d]$. The key differences from Huang et al. (2024) are threefold:

- Our cluster radius and δ are constants independent of n , rather than vanishing quantities $o_n(1)$ as in Huang et al. (2024).
- We carefully handle the probabilistic dependence among clusters extracted in different iterations, allowing the entire algorithm to operate using only four disjoint vertex partitions, instead of n^c partitions (for some constant $c > 0$) as required in Huang et al. (2024). This modification removes *one of the two sources of error degradation* Huang et al. (2024), namely the need to breaking the vertex set into n^c batches.
- Since we extract only constant-radius clusters, for each vertex pair (v, w) we need only compute their number of common neighbors over a subset of vertices V_{cn} with size $|V_{\text{cn}}| = \Theta(s_n^{-2} \log^2(n))$, which is of order $\log^2(n)$ when $s_n = 1$, comparing with $|V_{\text{cn}}| = n^{1-c}$ in Huang et al. (2024). This yields a substantial computational improvement in the local edge-counting part of the algorithm, reducing it from $O(n^3)$ in Huang et al. (2024) to $O(n^2 \text{polylog}(n))$ in our algorithm. The overall running time in Theorem 1.6 remains $O(n^3)$ because of the final all-pairs shortest-path computation.

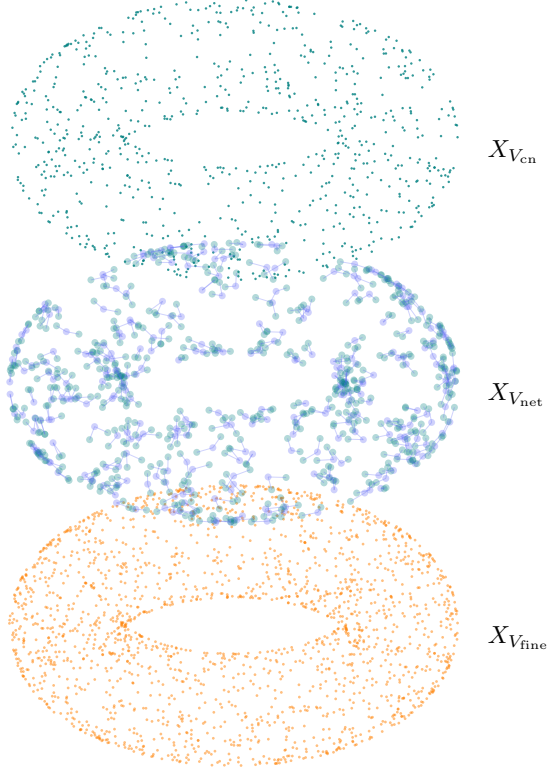


Figure 4: In the diagram, the vertex set $\mathbf{V}$ is partitioned into three disjoint subsets: V_{cn} , V_{net} , and V_{fine} . The first two subsets are used in **Stage 1**, where a constant-radius cluster net is constructed over the latent positions of vertices in V_{net} based on common-neighbor counts within V_{cn} . In **Stage 2**, for each vertex $v \in V_{\text{fine}}$, a nearby cluster center u_k from Stage 1 is identified (via $N_{U_k}(v)$). By leveraging the orthogonal clusters around u_k , one can estimate the distance between X_v and any other vertex's latent position X_w using the *multiple-cluster-difference* method. This allows us to collect all $w \in V_{\text{fine}}$ such that $|X_v X_w| \leq \xi$ to form a cluster around v with balanced-error radius ξ . Once all balanced-error clusters have been constructed via edge counting, the distance estimates are obtained through edge counting from fine clusters to vertices.

Stage 2: Local refinement. In the second stage, we use a single new batch of vertices. We may assume that for every vertex v , there exists a cluster center u_k such that $|X_v X_{u_k}| \leq \delta$. We then employ the multiple-cluster-difference method to extract a refined cluster centered precisely at v , with radius

$$\eta = O\left(\left(\frac{\log n}{s_n n}\right)^{1/(d+2)}\right) \gg \sqrt{\frac{\log n}{s_n n}}.$$

While smaller clusters can be extracted around each vertex, the key is to select η that balances the radius error and the fluctuation error in the cluster edge density method. Once such clusters are obtained, we can estimate $|X_v X_w|$ for every pair of vertices v, w up to an additive error of order $O((\log^2 n / (s_n n))^{1/(d+2)})$, whenever $|X_v X_w|$ lies within the bi-Lipschitz regime of p . Finally, we apply a shortest-path computation (e.g., Dijkstra's algorithm) to recover all pairwise distance estimates. With the second stage, we eliminate the other source of error degradation present in [Huang et al. \(2024\)](#), which is not capable to extracting optimal error-balanced clusters.

Our Algorithm in the Embedded case. We believe that our algorithms and analysis carry over also to the embedded case analyzed in [Huang et al. \(2024\)](#). Thus we believe that the statement of our main theorem also holds for random graphs sampled according to

the Euclidean distance between embedded points, where we can recover these Euclidean distances under the same assumptions and same error bounds as in our main theorem, with one caveat on the Bi-Lipschitz radius of p . We leave the verification of this to future work.

1.3.4. TRIANGLE COMPARISON, A BRIDGE BETWEEN THE LOCAL STRUCTURE OF M AND THE FLAT EUCLIDEAN SPACE.

Although the Nash embedding theorem ensures that any Riemannian manifold can be embedded into a higher-dimensional Euclidean space, our setting differs fundamentally from that of [Huang et al. \(2024\)](#). In their framework, edge probabilities are determined by Euclidean distances in the ambient space, whereas in ours they depend on geodesic distances within the manifold. Consequently, even after embedding, Euclidean and geodesic distances may diverge significantly, which necessitates working directly with the intrinsic Riemannian structure of M .

We use the exponential map to identify a small metric ball around p with a ball in the tangent space $T_p M$, and we write $\hat{x}$ for the tangent vector at p pointing to x . The precise definitions of $r_{\text{inj}}(M)$, the tangent representative $\hat{x}$, the model spaces M_κ^d , the opposite-side function $\gamma^\kappa(\theta; a, b)$, and the comparison angles $\angle^{\pm\kappa}(p_y^x)$ are collected in [Appendix B.1](#).

Consider two nearby points x, y . When M is flat, the geodesic distance is the Euclidean distance between their tangent representatives. A basic recurring task in the paper is to estimate how much the geodesic distance $|x y|$ can differ from this Euclidean proxy under the sectional curvature bound; let us say that there exists $\kappa > 0$ such that the sectional curvature K of M at any 2-plane σ in $T_p M$ for every $p \in M$ satisfies

$$-\kappa \leq K(\sigma) \leq \kappa.$$

(The existence of such a κ is guaranteed when M is compact.) Rather than expanding the exponential map and tracking higher-order error terms, we use triangle-comparison techniques. Specifically, we compare the geodesic triangle with its counterpart in a model space of constant curvature. The Rauch Comparison Theorem and Toponogov’s Triangle Comparison Theorem (see e.g. [Cheeger and Ebin \(2008\)](#)) translate the curvature bound into precise inequalities for side lengths and angles, stated formally in [Lemma B.4](#).

These comparison bounds form a quantitative bridge between the local geometry of M and that of its tangent plane. They let us compare the two spaces on a genuinely local, rather than merely infinitesimal, scale. Equipped with these estimates we may treat M as *almost flat* in a sufficiently small neighborhood of p , which in turn allows us to use many arguments from linear algebra.

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Outline of the paper. The appendix is organized as follows.

- Appendix A introduces some basic notions and events that will be used throughout the paper.
- Appendix B presents several geometric estimates on Riemannian manifolds that will be used in the analysis.
- Appendix C states and proves the results on cluster extraction through common-neighbor counts, which form the basis of our distance estimation algorithm.
- Appendix D presents the approximate orthogonal-basis construction.
- Appendix E presents point navigation via an approximate orthogonal basis.
- Appendices F and G illustrate the two stages of the distance-estimation algorithm.
- Appendix H concludes the proof of our main theorem by combining the results from previous appendices.
- Appendix I collects several standard results on Riemannian geometry used in the paper.
- Appendix J proves the lower bound result (Theorem 1.7).

Appendix A. Basic Notions and Events

Without loss of generality, throughout the paper we assume $\mathbf{V}$ is the vertex set of the random geometric graph $G \sim G(n, M, \mu, p, \mathbf{s}_n)$. For simplicity, we assume $|\mathbf{V}|$ is a constant multiple of n , instead of n , so that we can partition $\mathbf{V}$ into several disjoint subsets of equal size when needed. In particular, we assume $|\mathbf{V}| = 4n$ throughout the paper, which does not affect the statement of our main theorem (Theorem 1.6). Further, throughout the paper, we assume that the sparsity parameter $\mathbf{s}_n$ satisfies

$$\mathbf{s}_n^2 n = \omega(\log^2 n).$$

For points in any metric space under discussion and vertex sets $A, B \subseteq \mathbf{V}$, we use the notation

$$B_r(p) := \{q : \text{dist}(q, p) < r\}, \quad (4)$$

$$E(A, B) := \{\{a, b\} : a \in A, b \in B, a \sim b\}. \quad (5)$$

Below we define some basic events that will be used in the proofs of our main results and show that they hold with high probability.

Definition A.1 (Normalized common neighbors) *Let $U, V \subseteq \mathbf{V}$. We define the normalized number of common neighbors of V in U by*

$$\mathbf{N}_U(V) := \frac{|\{u \in U : v \sim u \text{ for all } v \in V\}|}{(\mathbf{s}_n)^{|V|} |U|}. \quad (6)$$

For a singleton $V = \{v\}$ we write $\mathbf{N}_U(v)$, and for a pair $V = \{v, w\}$ we write $\mathbf{N}_U(v, w)$. Further, for a singleton v , we also define the (conditional) expectation

$$\mathbf{p}_U(v) := \frac{1}{|U|} \sum_{u \in U} \mathbf{p}(|X_v X_u|), \quad (7)$$

so that $\mathbb{E}[\mathbf{N}_U(v) \mid X_v, X_U] = \mathbf{p}_U(v)$. Accordingly, we also define a notion of fluctuation error ε_U that depends on $|U|$:

$$\varepsilon_U := \frac{\log n}{\sqrt{s_n |U|}}, \quad \text{and} \quad \varepsilon_m := \frac{\log n}{\sqrt{s_n m}}. \quad (m \geq 1). \quad (8)$$

Lemma A.2 (Edge fluctuation event) *Let $U, V \subseteq \mathbf{V}$ be disjoint with $|V| \leq n$. Define*

$$\mathcal{E}_{\text{navi}}(U, V) := \left\{ \forall v \in V : |\mathbf{N}_U(v) - \mathbf{p}_U(v)| \leq \varepsilon_U \right\}. \quad (9)$$

Then for all fixed realizations $X_V = x_V, X_U = x_U$,

$$\Pr(\mathcal{E}_{\text{navi}}(U, V)^c \mid X_V = x_V, X_U = x_U) \leq n^{-\omega(1)}.$$

The above bound follow simply from the union bound and Chernoff bound:

Lemma A.3 (Chernoff Bound) *Let $Y = \sum_{i=1}^n Y_i$ be the sum of independent Bernoulli random variables with $\mu = \mathbb{E}[Y]$. Then for any $0 < t < \mu$,*

$$\Pr[|Y - \mu| \geq t] \leq 2 \exp\left(-\frac{t^2}{3\mu}\right).$$

Proof Fix x_V, x_U . For each $v \in V$,

$$\mathbf{N}_U(v) = \frac{1}{s_n |U|} \sum_{u \in U} \mathbf{1}\{\mathcal{U}_{v,u} < s_n \mathbf{p}(|X_v X_u|)\},$$

is a sum of independent Bernoulli random variables conditioned on X_v, X_U , normalized by $\Delta := s_n |U|$ and with mean $\mathbf{p}_U(v)$. By Chernoff bound, we have

$$\begin{aligned} \Pr(|\mathbf{N}_U(v) - \mathbf{p}_U(v)| \geq \varepsilon_U \mid X_v, X_U) &\leq \Pr(|\mathbf{N}_U(v) - \mathbf{p}_U(v)| \geq \varepsilon_U \mathbf{p}_U(v) \mid X_v, X_U) \\ &\leq 2 \exp\left(-\frac{\varepsilon_U^2 \Delta^2}{3 \Delta \mathbf{p}_U(v)}\right) = 2 \exp(-\log^2 n / 3), \end{aligned}$$

where we used the fact that $\mathbf{p}_U(v) \leq 1$. Next, applying the union bound over $v \in V$ yields the claim. $\blacksquare$

Definition A.4 (Cluster event) *For $u \in U \subseteq \mathbf{V}$ and $\eta > 0$, we define the event*

$$\mathcal{E}_{\text{clu}}(\eta, U, u) := \left\{ \forall u' \in U, |X_{u'} X_u| \leq \eta \right\}. \quad (10)$$

So, if $\mathcal{E}_{\text{clu}}(\eta, U, u)$ and $\mathcal{E}_{\text{navi}}(U, v)$ hold, then the normalized number of common neighbors $N_U(v)$ can be used to estimate the latent distance $|X_v X_u|$, with error coming from both the cluster radius η and the fluctuation error ε_U .

Definition A.5 (*Size Calibration margin*) For a set $U \subseteq \mathbf{V}$, we say that the size of U satisfies the calibration margin with parameter $\eta > 0$ if

$$\varepsilon_U \leq \ell_p \eta. \quad (11)$$

Lemma A.6 (Calibration toolkit: single, annulus) Let $\rho \in U \subseteq \mathbf{V}$. Suppose the size of U satisfies the calibration margin (11) with parameter $0 < \eta < r_G$, and the events $\mathcal{E}_{\text{clu}}(\eta, U, \rho)$ and $\mathcal{E}_{\text{navi}}(U, w)$ hold. Then:

(i) *Single-cluster calibration.*

$$|N_U(w) - p(|X_w X_\rho|)| \leq L_p \eta + \varepsilon_U \leq 2L_p \eta. \quad (12)$$

If moreover either $N_U(w) \geq p(r_G)$ or $|X_w X_\rho| \leq r_G$, then

$$||X_w X_\rho| - p^{-1}(N_U(w))| \leq \eta + \ell_p^{-1} \varepsilon_U \leq 2\eta.$$

If $N_U(w) < p(r_G)$, then $|X_w X_\rho| > r_G - 2\eta$.

(ii) *Annulus-threshold equivalence.* Fix $r \leq r_G$ and $\alpha \in [0, r]$.

$$\begin{aligned} N_U(w) \leq p(r - \alpha) &\Rightarrow |X_w X_\rho| \geq r - \alpha - 2\eta \\ N_U(w) \geq p(r + \alpha) &\Rightarrow |X_w X_\rho| \leq r + \alpha + 2\eta \\ ||X_w X_\rho| - r| \leq \alpha &\Rightarrow p(r + \alpha + 2\eta) \leq N_U(w) \leq p(r - \alpha - 2\eta). \end{aligned} \quad (13)$$

Proof Preparation. Throughout we use that p is nonincreasing, L_p -Lipschitz on $[0, \text{diam}(M)]$, and bi-Lipschitz on $[0, 16r_G]$ with lower constant ℓ_p . If $\mathcal{E}_{\text{clu}}(\eta, U, \rho)$ holds, then for any w ,

$$p(|X_w X_\rho| + \eta) \leq p_U(w) \leq p(|X_w X_\rho| - \eta). \quad (14)$$

This is immediate from the triangle inequality and the monotonicity of p . If $\mathcal{E}_{\text{navi}}(U, w)$ holds, then by definition

$$|N_U(w) - p_U(w)| \leq \varepsilon_U. \quad (15)$$

Single-cluster calibration. Combining (14) and (15) and using the L_p -Lipschitz property, let $D = |X_w X_\rho|$. Then

$$|N_U(w) - p(|X_w X_\rho|)| \leq \varepsilon_U + \max \left\{ |p(D + \eta) - p(D)|, |p(D - \eta) - p(D)| \right\} \leq \varepsilon_U + L_p \eta.$$

This proves the first inequality in (12). Since $\varepsilon_U \leq \ell_p \eta \leq L_p \eta$, we also get $|N_U(w) - p(D)| \leq 2L_p \eta$. Now consider the inversion bound. If $N_U(w) \geq p(r_G)$, then

$$p(D - \eta) \geq p_U(w) \geq N_U(w) - \varepsilon_U \geq p(r_G) - \varepsilon_U \Rightarrow D \leq r_G + \eta + \ell_p^{-1} \varepsilon_U < 16r_G.$$

On the other hand, if $D \leq r_G$, then

$$\mathbf{N}_U(w) \geq \mathbf{p}_U(w) - \varepsilon_U \geq p(D + \eta) - \varepsilon_U \geq p(r_G + \eta) - \varepsilon_U \Rightarrow p(\mathbf{N}_U(w)) \leq r_G + \eta + \ell_p^{-1} \varepsilon_U < 16r_G.$$

In either case, we have $D, \mathbf{N}_U(w) \in [0, 16r_G]$, so the low-Lipschitz property applies:

$$|D - p^{-1}(\mathbf{N}_U(w))| \leq \ell_p^{-1} |p(D) - \mathbf{N}_U(w)| \leq \ell_p^{-1} \varepsilon_U + \ell_p^{-1} L_p \eta \leq \ell_p^{-1} \varepsilon_U + \eta \leq 2\eta.$$

Finally, if $\mathbf{N}_U(w) < p(r_G)$, a similar argument shows $p(D + \eta) \leq p(r_G) + \varepsilon_U$ implying $D > r_G - \eta - \ell_p^{-1} \varepsilon_U > r_G - 2\eta$.

Annulus-threshold equivalence. Fix $r \leq r_G$ and $\alpha \in [0, r]$. Assume $\mathbf{N}_U(w) \leq p(r - \alpha)$. Then,

$$p(D + \eta) \leq \mathbf{p}_U(w) \leq \mathbf{N}_U(w) + \varepsilon_U \leq p(r - \alpha) + \varepsilon_U \leq p(r - \alpha - \ell_p^{-1} \varepsilon_U) \Rightarrow D \geq r - \alpha - 2\eta.$$

Similarly, if $\mathbf{N}_U(w) \geq p(r + \alpha)$, then invoking the inequalities in the other direction leads to

$$D \leq r + \alpha + 2\eta.$$

This proves the first implication in (13). Now we assume $|D - r| \leq \alpha$. Then,

$$\mathbf{N}_U(w) \leq \mathbf{p}_U(w) + \varepsilon_U \leq p(D - \eta) + \varepsilon_U \leq p(r - \alpha - \eta) + \varepsilon_U \leq p(r - \alpha - 2\eta),$$

and similarly in the other direction. From (14),

$$p(D + \eta) \leq \frac{1}{|U|} \sum_{u \in U} p(DX_w X_u) \leq p(D - \eta).$$

Adding/subtracting ε_U via (15) and using monotonicity,

$$p(r + \alpha + \eta) - \varepsilon_U \leq \mathbf{N}_U(w) \leq p(r - \alpha - \eta) + \varepsilon_U.$$

This matches the claimed bounds. ■

Definition A.7 (Common neighbor as inner product) For points $x, y \in M$, we define the following inner product-like quantity that measures the common neighbor probability between x and y

$$\langle x, y \rangle := \mathbb{E}_{Z \sim \mu} p(|x|Z|) p(|y|Z|) = \int_M p(|x|z|) p(|y|z|) d\mu(z), \quad (16)$$

where in particular, it is the inner product of the functions $p(|x|\cdot|)$ and $p(|y|\cdot|)$ in the Hilbert space $L^2(M, \mu)$. Moreover,

$$\langle X_i, X_j \rangle$$

is precisely the probability that a third vertex k is in the common neighbor of i and j (Definition 1.4) conditioned on the latent positions X_i and X_j .

Lemma A.8 Suppose V, U are two disjoint set of vertices in our random geometric graph model (Definition 1.4) with $|V| \leq n$. Consider the event

$$\mathcal{E}_{\text{cn}}(U, V) := \left\{ \forall v, w \in V, \left| \mathbf{N}_U(v, w) - \langle X_v, X_w \rangle_{\text{cn}} \right| \leq \frac{\log(n)}{\sqrt{s_n^2 |U|}} \right\}, \quad (17)$$

which is an event of $\mathcal{U}_{U,V}$ and the latent points X_V, X_U . If

$$s_n^2 |U| = \omega(\log(n)),$$

then

$$\Pr \left(\mathcal{E}_{\text{cn}}(U, V)^c \mid X_V = x_V \right) = n^{-\omega(1)} \quad \forall x_V \in M^{|V|}.$$

Proof The proof is similar to that of Lemma A.2. It is an application of the Chernoff bound together with the union bound over $\binom{|V|}{2}$ pairs of vertices in V . Let us fix any realization of the latent points $X_V = x_V$. Fix $\{v, w\} \in \binom{|V|}{2}$. Observe

$$\mathbf{N}_U(v, w) = \frac{1}{s_n^2 |U|} \sum_{u \in U} \underbrace{\mathbf{1} \left(\mathcal{U}_{v,u} < s_n \mathbf{p}(|X_v X_u|) \right) \mathbf{1} \left(\mathcal{U}_{w,u} < s_n \mathbf{p}(|X_w X_u|) \right)}_{:= Z_u}.$$

Notice that $\{Z_u\}_{u \in U}$ are independent Bernoulli random variables with mean

$$\mathbb{E}_{X_u, \mathcal{U}_u, \{v, w\}} [Z_u \mid X_v, X_w] = \mathbb{E}_{X_u} \left[s_n^2 \mathbf{p}(|X_v X_u|) \mathbf{p}(|X_w X_u|) \mid X_v, X_w \right] = s_n^2 \langle X_v, X_w \rangle_{\text{cn}},$$

which implies that

$$\mathbb{E}_{X_u, \mathcal{U}_u, \{v, w\}} [\mathbf{N}_U(v, w) \mid X_v, X_w] = \langle X_v, X_w \rangle_{\text{cn}}.$$

The standard Chernoff bound gives

$$\begin{aligned} & \Pr \left(\left| \mathbf{N}_U(v, w) - \langle X_v, X_w \rangle_{\text{cn}} \right| \geq \frac{\log(n)}{\sqrt{s_n^2 |U|}} \mid X_V = x_V \right) \\ &= \Pr \left(\left| \sum_{u \in U} Z_u - |U| s_n^2 \langle X_v, X_w \rangle_{\text{cn}} \right| \geq \log(n) \sqrt{s_n^2 |U|} \mid X_V = x_V \right) \leq 2 \exp(-c \log^2(n)) = n^{-\omega(1)}, \end{aligned}$$

where we used the fact that $\langle X_v, X_w \rangle_{\text{cn}} \leq 1$. Within the complement of the event described above, we have, after normalization, the event $\mathcal{E}_{\text{cn}}(U, V)$ holds. ■

Lemma A.9 Suppose $\{X_v\}_{v \in V}$ are i.i.d. random points sampled from a distribution μ on a manifold M and $|V| = n$. The event

$$\mathcal{E}_{\text{pt}}(V) := \left\{ \left| \{X_i\}_{i \in [n]} \cap B_\varepsilon(p) \right| \geq \mu_{\min}(\varepsilon/3) \frac{n}{2} \quad \forall p \in M, \left(\frac{\log(n)}{n} \right)^{1/d} \leq \varepsilon \leq r_\mu \right\}, \quad (18)$$

holds with probability $1 - n^{-\omega(1)}$.

The above lemma follows from standard volumetric arguments and Chernoff bound; see e.g. Huang et al. (2024) for a similar proof.

A.1. Additional Notation

Assumption A.10 (Parameter Configurations) *In the algorithm, we will choose several distance parameters: η, δ, r corresponding to cluster radius, net radius, and orthonormal frame radius respectively. Further, we also have a cluster size parameter m (a desired lower bound on the size of an extracted cluster). For any gap parameter $c \in [0, 1)$ which might depends on $\ell_p, L_p, \mu_{\min}(\cdot)$, and d , but not on n , we say the tuples (r, δ, η, m) satisfy the parameter configurations with gap c if*

$$r \leq c \cdot r_G, \quad \delta = c \cdot r, \quad \eta = c \cdot \delta \quad \text{and} \quad \varepsilon_m \leq c\eta^2. \quad (19)$$

Appendix B. Triangle comparison

Here we collect the main tools from Riemannian geometry that allow us to compare distances and angles in a Riemannian manifold with those in model spaces of constant curvature. We first fix the notation for tangent representatives, model spaces, opposite-side functions, and comparison angles. The main result is the following Triangle Comparison Lemma, which is a direct consequence of the Rauch Comparison Theorem (see e.g. Cheeger and Ebin (2008)). At the end of this section, we also include a regularity lemma (Lemma B.9) for measuring the change of edge counts from a cluster to a single vertex when perturbing the latent position of the vertex slightly.

B.1. Model-space notation

Consider a Riemannian manifold (M, g) . For each point $p \in M$, the *exponential map* at p is the smooth map

$$\exp_p : T_p M \longrightarrow M,$$

which sends a vector $v \in T_p M$ to the point reached, at parameter time 1, by the geodesic starting at p with initial velocity v . The *injectivity radius* of M is defined by

$$r_{\text{inj}}(M) := \sup \left\{ r > 0 : \exp_p|_{B_r(\mathbf{0})} \text{ is a diffeomorphism for every } p \in M \right\}. \quad (20)$$

For convenience, whenever $p \in M$ and $x \in B_{r_{\text{inj}}(M)}(p) \subseteq M$, we set

$$\hat{x} = (\hat{x})_p := \exp_p^{-1}(x) \in T_p M. \quad (21)$$

A standard consequence of the Gauss lemma (see Proposition I.1 and see e.g. Cheeger and Ebin (2008)) is that, for every $p \in M$, the exponential map $\exp_p$ maps the open ball $B_{r_{\text{inj}}(M)}(0) \subseteq T_p M$ diffeomorphically onto the open ball $B_{r_{\text{inj}}(M)}(p) \subseteq M$. For each $x \in B_{r_{\text{inj}}(M)}(p)$, the curve

$$t \mapsto \exp_p(t \hat{x}), \quad t \in [0, 1],$$

is the unique minimizing geodesic from p to x . In particular, the Riemannian distance satisfies

$$|p x| = \|\hat{x}\|.$$

Definition B.1 (Model spaces) For any $\kappa \in \mathbb{R}$, let M_κ^d be the d -dimensional, simply connected, complete Riemannian manifold whose sectional curvature is identically κ . The three standard cases are summarized below:

Curvature κ	Name of model space M_κ^d	Concrete realization	Diameter ϖ_κ
$\kappa > 0$	d -sphere of radius $1/\sqrt{\kappa}$	$\frac{1}{\sqrt{\kappa}}\mathbb{S}^d \subseteq \mathbb{R}^{d+1}$	$\frac{\pi}{\sqrt{\kappa}}$
$\kappa = 0$	Euclidean d -space	$\mathbb{R}^d$	∞
$\kappa < 0$	Hyperbolic d -space of curvature κ	$\mathbb{H}_\kappa^d$	∞

In what follows, when the dimension d is clear from the context, we may write M_κ instead of M_κ^d , omitting the superscript d .

Definition B.2 (Opposite-side function) Let $\kappa \in \mathbb{R}$, $\theta \in [0, \pi]$, and $a, b > 0$ with $a+b < \varpi_\kappa$. We write

$$\Upsilon^\kappa(\theta; a, b)$$

for the length of the side opposite the angle θ in a geodesic triangle whose two adjacent sides forming the angle θ have lengths a and b in the model space M_κ^d .

The assumption $a + b < \varpi_\kappa$ guarantees that the corresponding geodesic triangle is well-defined when $\kappa > 0$ in the positively curved model space M_κ^d .

Definition B.3 (Comparison angles) Let $p, x, y \in M$ with $x, y \in B_{r_{\text{inj}}(M)/2}(p) \setminus \{p\}$. We define

$$\angle(p_y^x) := \angle(\hat{x}, \hat{y}) = \arccos\left(\frac{\langle \hat{x}, \hat{y} \rangle}{\|\hat{x}\| \|\hat{y}\|}\right),$$

the angle at p of the geodesic triangle $\triangle pxy$ in M . Given $\kappa > 0$ and assuming $|px| + |py| < \varpi_\kappa$, we further set

$$\angle^\kappa(p_y^x) \quad \text{and} \quad \angle^{-\kappa}(p_y^x)$$

to be, respectively, the angles at $\tilde{p}$ of the comparison triangle $\triangle \tilde{p}\tilde{x}\tilde{y} \subseteq M_\kappa$ and of the corresponding triangle in $M_{-\kappa}$, that is, the unique triangle in the model space whose side lengths equal $|px|$, $|py|$, and $|xy|$.

The requirement $x, y \in B_{r_{\text{inj}}(M)/2}(p)$ guarantees that $|px|$, $|py|$, and $|xy|$ are all less than $r_{\text{inj}}(M)$, so the distance-minimizing geodesics are unique; hence there is no ambiguity in the definition of the corresponding geodesic triangles in M .

Lemma B.4 Let $\kappa > 0$ be a positive constant. Let (M, g) be a compact d -dimensional Riemannian manifold whose sectional curvatures satisfy

$$-\kappa \leq K(\sigma) \leq \kappa,$$

for every 2-plane σ in the tangent bundle TM . Fix $p \in M$ and set

$$r := \min\{r_{\text{inj}}(M), \pi/\sqrt{\kappa}\}.$$

Consider $x, y \in B_{r/2}(p)$ and write $\theta := \angle(p_y^x)$. Then

$$\Upsilon^\kappa(\theta; |px|, |py|) \leq |xy| \leq \Upsilon^{-\kappa}(\theta; |px|, |py|) \quad (22)$$

and

$$\angle^{-\kappa}(p_y^x) \leq \angle(p_y^x) \leq \angle^\kappa(p_y^x). \quad (23)$$

It is also worth recalling the *laws of cosines* for model spaces of constant curvature κ , which relate the side lengths and an angle of a geodesic triangle.

Fact B.5 (The laws of cosines for model spaces, see e.g. [Alexander et al. \(2024\)](#))

Let $\kappa > 0$ and consider a geodesic triangle in the spherical model space M_κ with side lengths a, b, c satisfying

$$a, b, c < \frac{1}{2}\varpi_\kappa = \frac{\pi}{2\sqrt{\kappa}}.$$

If θ denotes the angle opposite the side of length c , then

$$\cos(\sqrt{\kappa}c) = \cos(\sqrt{\kappa}a)\cos(\sqrt{\kappa}b) + \sin(\sqrt{\kappa}a)\sin(\sqrt{\kappa}b)\cos(\theta). \quad (24)$$

For a geodesic triangle in the hyperbolic model space $M_{-\kappa}$ ($\kappa > 0$) with side lengths a, b, c and θ again the angle opposite the side of length c , one has

$$\cosh(\sqrt{\kappa}c) = \cosh(\sqrt{\kappa}a)\cosh(\sqrt{\kappa}b) - \sinh(\sqrt{\kappa}a)\sinh(\sqrt{\kappa}b)\cos(\theta). \quad (25)$$

Following from the Triangle Comparison Lemma [B.4](#) and the laws of cosines above, we have a few lemmas regarding angles and distances which essentially arrive from expanding the laws of cosines in Taylor series.

Lemma B.6 *Let (M, g) be a Riemannian manifold whose sectional curvatures are uniformly bounded in absolute value by a constant $\kappa > 0$. Suppose p, q, x be points in M such that*

$$0 \leq |px|, |pq| < \frac{1}{4} \min\{\varpi_\kappa, r_{\text{inj}}(M)\} \quad \text{and} \quad |pq| \leq \frac{1}{4}|px|.$$

Expressing

$$a := |px|, \quad b := |pq|, \quad c := |qx|, \quad \text{and} \quad \theta := \angle(p_q^x).$$

Then

$$-\frac{7}{6}\frac{b^2}{a} - \frac{\kappa b^2}{3} \cdot b|\cos(\theta)| \leq a - c - b\cos(\theta) \leq \pi\frac{b}{a} \cdot b|\cos(\theta)|.$$

Remark B.7 *In the flat Euclidean plane, the ordinary law of cosines gives*

$$c^2 = a^2 + b^2 - 2ab\cos\theta \implies c = a - b\cos\theta + O(b^2) \quad (b \rightarrow 0, a \text{ fixed}).$$

Hence $a - c - b\cos\theta$ is the second-order remainder in the Taylor expansion of c with respect to b at $b = 0$. Our goal is to show that, with the curvature correction, how this second-order remainder is controlled.

Lemma B.8 Fix $\kappa > 0$. Consider a geodesic triangle in M_κ with adjacent sides a, b and angle θ between them. Assume

$$0 < a, b < \frac{1}{4} \varpi_\kappa \quad \text{and} \quad c := \Upsilon^\kappa(\theta; a, b) \leq \frac{1}{2} a.$$

Then

$$\theta \leq 2 \frac{c}{a}.$$

Given these lemmas are standard in Riemannian geometry and not to detract from the main flow of the paper, we postpone their proofs to Appendix I.

Lemma B.9 (Edge Counting Regularity) Let (M, g) be a Riemannian manifold whose sectional curvatures are uniformly bounded in absolute value by a constant $\kappa > 0$. Let $p, x, q \in M$ be three points in a Riemannian manifold M with

$$|px|, |pq| < \frac{1}{8} \min\{r_{\text{inj}}(M), \varpi_\kappa\} \quad \text{and} \quad 16 \frac{|pq|}{|px|} \leq |\cos(\angle(p_x^q))|.$$

Suppose $x' \in M$ is a point satisfying

$$16 \frac{|xx'|}{|px|} \leq |\cos(\angle(p_x^q))|.$$

Then, the following holds:

$$\frac{1}{2} \leq \frac{|px'| - |qx'|}{\cos(\angle(p_x^q))|pq|} \leq 2. \quad (26)$$

Furthermore, with the additional assumption that

$$|px| \leq \frac{1}{2} r_p,$$

we have

$$\frac{1}{2} \ell_p \leq \frac{p(|qx'|) - p(|px'|)}{\cos(\angle(p_x^q))|pq|} \leq 2L_p.$$

Proof Cosine value comparison. We first invoke Lemma B.4 to compare the angle $\angle(p_{x'}^x)$ with the model angle $\angle^\kappa(p_{x'}^x)$, and then Lemma B.8 to obtain the following estimate on the angle $\angle(p_{x'}^x)$:

$$\angle(p_{x'}^x) \leq \angle^\kappa(p_{x'}^x) \leq 2 \frac{|xx'|}{|px|},$$

which in term implies

$$|\angle(p_x^q) - \angle(p_{x'}^q)| \leq \angle(p_{x'}^x) \leq 2 \frac{|xx'|}{|px|}.$$

Relying on the fact that $t \mapsto \cos(t)$ is a Lipschitz function with constant 1,

$$|\cos(\angle(p_x^q)) - \cos(\angle(p_{x'}^q))| \leq 2 \frac{|xx'|}{|px|} \leq \frac{1}{8} |\cos(\angle(p_x^q))|,$$

where the last inequality follows from the assumption $16 \frac{|xx'|}{|px|} \leq |\cos(\angle(p_x^q))|$. Therefore, we conclude that $\cos(\angle(p_x^q))$ and $\cos(\angle(p_{x'}^q))$ have *the same sign* and

$$\frac{7}{8} |\cos(\angle(p_x^q))| \leq |\cos(\angle(p_{x'}^q))| \leq \frac{9}{8} |\cos(\angle(p_x^q))|. \quad (27)$$

Invoking Lemma B.6. We apply Lemma B.6 to the triple (p, q, x') . To do that, we still need to show

$$|px'| < \frac{1}{4} \min\{r_{\text{inj}}(M), \varpi_\kappa\} \quad \text{and} \quad |pq| < \frac{1}{4} |px'|. \quad (28)$$

To drive this, we first note that the $16 \frac{|xx'|}{|px|} \leq |\cos(\angle(p_x^q))| \leq 1$ implies

$$\frac{15}{16} |px| \leq |px'| \leq \frac{17}{16} |px|. \quad (29)$$

Combining this with the assumption $|px| < \frac{1}{8} \min\{r_{\text{inj}}(M), \varpi_\kappa\}$ and $|pq| \leq \frac{1}{8} |px|$ leads to (28) and a slightly stronger estimate

$$|pq| \leq \frac{2}{15} |px'|. \quad (30)$$

Now expressing

$$a := |px'|, \quad b := |pq|, \quad c := |qx'|, \quad \text{and} \quad \theta := \angle(p_q^{x'})$$

and invoking Lemma B.6, we have

$$-\frac{7}{6} \frac{b^2}{a} - \frac{\kappa b^2}{3} \cdot b |\cos(\theta)| \leq a - c - b \cos(\theta) \leq \pi \frac{b}{a} \cdot b |\cos(\theta)|. \quad (31)$$

Simplifying the estimates. We first claim that

$$\pi \frac{b}{a} \cdot b |\cos(\theta)| \leq \frac{b}{2} |\cos(\theta)| \quad \text{and} \quad \frac{7}{6} \frac{b^2}{a} + \frac{\kappa b^2}{3} \cdot b |\cos(\theta)| \leq \frac{b}{2} |\cos(\theta)|.$$

The first inequality is a straightforward consequence of (30) and the fact that $\frac{2}{15}\pi \leq 0.42$. By (28),

$$\frac{\kappa b^2}{3} = \frac{\kappa a^2}{3} \frac{b^2}{a^2} \leq \frac{1}{16 \cdot 3} \frac{1}{16} \frac{b}{a}.$$

Also, our assumption $16 \frac{|xx'|}{|px|} \leq |\cos(\angle(p_x^q))|$, (29), and (27) imply

$$\frac{b}{a} = \frac{|pq|}{|px'|} = \frac{|pq|}{|px|} \cdot \frac{|px|}{|px'|} \leq \frac{1}{16} |\cos(\angle(p_x^q))| \cdot \frac{16}{15} \leq \frac{1}{16} \frac{9}{8} |\cos(\theta)| \cdot \frac{16}{15} = \frac{3}{40} |\cos(\theta)|.$$

Hence,

$$\frac{7}{6} \frac{b^2}{a} \leq \frac{7}{80} b |\cos(\theta)|.$$

Combining these two estimates for the summands leads to the claim. Finally, the claim together with (31) implies

$$1 - 0.42 \leq \frac{a - c}{b \cos(\theta)} \leq 1 + 0.42,$$

regardless of the sign of $\cos(\theta)$. Unwrapping the definitions of a, b, c, θ , together with (27), we obtain the first statement of the lemma.

Final estimate on p . Notice that

$$\max\{|p x'|, |q x'|\} \leq \max\{|p x| + |x x'|, |q p| + |p x| + |x x'|\} \leq \left(\frac{1}{16} + 1 + \frac{1}{16}\right) |p x| \leq r_p,$$

where the last inequality follows from the additional assumption $|p x| \leq \frac{1}{8} r_p$. Within $[0, r_p]$, we can rely on the bi-Lipschitz continuity of p to obtain

$$\ell_p \leq \frac{p(|q x'|) - p(|p x'|)}{|p x'| - |q x'|} \leq L_p,$$

where we emphasize that due to p is monotone decreasing, $p(|q x'|) - p(|p x'|)$ and $|p x'| - |q x'|$ always have the same sign. Substituting this ratio into the first statement of the lemma, we obtain second statement of the lemma. ■

Appendix C. Common Neighbor Probability and cluster finding algorithm

Using the algebraic identity $(a - b)^2 = a^2 - 2ab + b^2$, we obtain the following proposition.

Proposition C.1 *For any points $x, y \in M$, we have*

$$\langle x, y \rangle_{\text{cn}} = \frac{\langle x, x \rangle_{\text{cn}} + \langle y, y \rangle_{\text{cn}}}{2} - \frac{1}{2} \int_M (p(|x z|) - p(|y z|))^2 d\mu(z). \quad (32)$$

The following lemma derives a quantitative estimate on the integral of the above identity.

Lemma C.2 *Recall from (1.5) that*

$$r_G = \frac{1}{16} \min \{r_p, r_{\text{inj}}(M), \varpi_\kappa, r_\mu\}.$$

For any $p, q \in M$, we have

$$\langle p, q \rangle_{\text{cn}} \leq \frac{\langle p, p \rangle_{\text{cn}} + \langle q, q \rangle_{\text{cn}}}{2} - c \cdot \min \{r_G^2, |p q|^2\}.$$

where $c = c_{\text{C.2}} := \mu_{\min}(r_G) \cdot \frac{\ell_p^2}{2\pi^2}$.

Let us postpone the proof to the end of the section. With the quantitative estimate, we can collect pairs (X_i, X_j) whose $\langle X_i, X_j \rangle_{\text{cn}}$ is close to $\frac{\langle X_i, X_i \rangle_{\text{cn}} + \langle X_j, X_j \rangle_{\text{cn}}}{2}$, which allows us to deduce that the distance $|X_i X_j|$ is small. Building from this we have our first algorithm.

Algorithm 1: GenerateCluster

Input : $U \subseteq \mathbf{V}$. $V \subseteq \mathbf{V}$, a subset of size between 2 and n .

$\eta > 0$.

Output: $W_{\text{gc}} \subseteq V$, a subset of vertices.

$i_{\text{gc}} \in W_{\text{gc}}$, a vertex.

Step 1. Sort $\{i, j\} \in \binom{V}{2}$ according to $N_U(i, j)$ from the largest to the smallest, and return a list $\{i_1, j_1\}, \{i_2, j_2\}, \dots, \{i_L, j_L\}$, where $L = \binom{|V|}{2} = \binom{V}{2}$.

Step 2. Let m be the largest positive integer such that

$$N_U(i_m, j_m) \geq N_U(i_1, j_1) - \frac{1}{2} c_{\text{C.2}} \eta^2,$$

where $c_{\text{C.2}}$ is the constant from Lemma C.2.

Step 3. Consider a graph G_{gc} with vertex set $V_{\text{gc}} := (\bigcup_{k \in [m]} \{i_k\}) \cup (\bigcup_{k \in [m]} \{j_k\})$ and edge set $E_{\text{gc}} := \{\{i_k, j_k\} : k \in [m]\}$.

Step 4. Take a pair $(W_{\text{gc}}, i_{\text{gc}})$ where $i_{\text{gc}} \in V_{\text{gc}}$ maximizes the size of neighbors in G_{gc} and $W_{\text{gc}} = \{j \in V_{\text{gc}} : \{i_{\text{gc}}, j\} \in E_{\text{gc}}\} \cup \{i_{\text{gc}}\}$.

return $(W_{\text{gc}}, i_{\text{gc}})$

Remark C.3 The common neighbor counts $N_U(i, j)$ for all pairs $\{i, j\} \in \binom{V}{2}$ are sub-entries of the matrix $A^\top A$, where A is the adjacency matrix restricted to the block $U \times V$. Using fast sparse matrix-matrix multiplication algorithms, the computation of $A^\top A$ can be performed in time $O(n^2 s_n^2 |U|)$ with probability $1 - o(1)$ assuming the concentration of degree on the graph, and converting A to a sparse representation requires $O(n|U|)$ time. Therefore, the overall running time of the algorithm is

$$O(n^2 (s_n^2 |U| + \log n)),$$

which is dominated by either the sorting step or by determining the common neighbor counts $N_U(i, j)$ for all pairs $\{i, j\} \in \binom{V}{2}$.

Definition C.4 ((η, m) -dense set) For $\eta > 0$ and a positive integer m , a subset of vertices $W \subseteq \mathbf{V}$ is called (η, m) -dense, if for every $w \in W$, the set

$$\left| \left\{ w' \in W : |X_w X_{w'}| \leq \eta \right\} \right| \geq m.$$

Proposition C.5 There exists a universal constant $C_{\text{C.5}} > 1$ such that the following holds. Suppose V, U are two disjoint subset of vertices in our random geometric graph model (Definition 1.4) with $|V| \leq n$ such that the events $\mathcal{E}_{\text{cn}}(U, V)$ holds. Let η be a positive parameter satisfying

$$C_{\text{C.5}} \left(\frac{\log(n)}{\sqrt{s_n^2 |U|}} \right)^{1/2} \leq \eta \leq r_G. \quad (33)$$

and set

$$m := \min_{i \in V} \left| \left\{ j \in V : |X_i X_j| \leq c\eta^2 \right\} \right| \quad (34)$$

where

$$c = c_{\text{C.5}} = \frac{1}{4} \frac{c_{\text{C.2}}}{\max\{L_p, 1\}}$$

and $c_{\text{C.2}}$ is the constant from Lemma C.2. In other words, V is a $(c\eta^2, m)$ -dense set by the definition above. Then, the output of Algorithm 1 returns a pair $(W_{\text{gc}}, i_{\text{gc}})$ such that the following holds:

$$\forall i \in W_{\text{gc}}, \quad |X_{i_{\text{gc}}} X_i| \leq \eta \text{ and } |W_{\text{gc}}| \geq m.$$

Proof First, from Cauchy–Schwarz inequality, we have

$$\max_{i,j \in V} \langle X_i, X_j \rangle_{\text{cn}} = \max_{i \in V} \langle X_i, X_i \rangle_{\text{cn}}.$$

Let $i_0 \in V$ be a vertex such that $\langle X_{i_0}, X_{i_0} \rangle_{\text{cn}} = \max_{i \in V} \langle X_i, X_i \rangle_{\text{cn}}$. For any $(i, j) \in \binom{V}{2}$, by the event $\mathcal{E}_{\text{cn}}(U, V)$ we have

$$\max_{i,j \in V} N_U(i, j) \leq \max_{i,j \in V} \langle X_i, X_j \rangle_{\text{cn}} + \frac{\log(n)}{\sqrt{s_n^2 |U|}} \leq \langle X_{i_0}, X_{i_0} \rangle_{\text{cn}} + \frac{\log(n)}{s_n^2 |U|}.$$

Lower bound on $|W_{\text{gc}}|$. Consider the set

$$S := \{j \in V \setminus \{i_0\} : |X_{i_0} X_j| \leq c\eta^2\}.$$

Therefore, for any $j \in S$, we have

$$\begin{aligned} N_U(i_0, j) &\geq \langle X_{i_0}, X_j \rangle_{\text{cn}} - \frac{\log(n)}{s_n^2 |U|} \geq \langle X_{i_0}, X_{i_0} \rangle_{\text{cn}} - L_p c\eta^2 - \frac{\log(n)}{\sqrt{s_n^2 |U|}} \\ &\geq \max_{(i,j) \in \binom{V}{2}} N_U(i, j) - L_p c\eta^2 - 2 \frac{\log(n)}{\sqrt{s_n^2 |U|}} \\ &\geq \max_{(i,j) \in \binom{V}{2}} N_U(i, j) - \frac{1}{2} c_{\text{C.2}} \eta^2, \end{aligned} \quad (35)$$

where the last inequality follows from our choice of c and setting $C_{\text{C.5}}$ sufficiently large.

Therefore, the collection of pairs $\{(i_0, j) : j \in S\}$ will be edges in the graph G_{gc} constructed in Algorithm 1. This implies that the number of neighbors of i_{gc} is at least the number of i_0 in G_{gc} , which is at least $|S| \geq m$ from the $(c\eta^2, m)$ -density assumption on V .

Upper bound on $|X_{i_{\text{gc}}} X_j|$ for $j \in W_{\text{gc}}$. Any pair $(i', j') \in \binom{V}{2}$ appears as an edge in the graph G_{gc} if and only if

$$N_U(i', j') \geq \max_{(i,j) \in \binom{V}{2}} N_U(i, j) - \frac{1}{2} c_{\text{C.2}} \eta^2.$$

First, replacing $N_U(i', j')$ by its expected value we have

$$\langle X_{i'}, X_{j'} \rangle_{\text{cn}} \geq \max_{(i,j) \in \binom{V}{2}} N_U(i, j) - \frac{1}{2} c_{\text{C.2}} \eta^2 - \frac{\log(n)}{\sqrt{s_n^2 n}}.$$

From the estimate (35), take any $j'' \in S$, we have

$$\begin{aligned} \max_{(i,j) \in \binom{V}{2}} N_U(i, j) - \frac{\log(n)}{\sqrt{s_n^2 n}} &\geq N_U(i_0, j'') - \frac{\log(n)}{\sqrt{s_n^2 n}} \\ &\stackrel{(35)}{\geq} \langle X_{i_0}, X_{i_0} \rangle_{\text{cn}} - L_{\text{p}} c \eta^2 - \frac{\log(n)}{\sqrt{s_n^2 n}} - \frac{\log(n)}{\sqrt{s_n^2 n}} \\ &\geq \langle X_{i_0}, X_{i_0} \rangle_{\text{cn}} - \frac{1}{2} c_{\text{C.2}} \eta^2, \end{aligned}$$

which implies that

$$\langle X_{i'}, X_{j'} \rangle_{\text{cn}} \geq \langle X_{i_0}, X_{i_0} \rangle_{\text{cn}} - c_{\text{C.2}} \eta^2 \geq \frac{\langle X_{i'}, X_{i'} \rangle_{\text{cn}} + \langle X_{j'}, X_{j'} \rangle_{\text{cn}}}{2} - c_{\text{C.2}} \eta^2.$$

By Lemma C.2, the above condition gives

$$|X_{i'} X_{j'}| \leq \eta.$$

■

For the proof of Lemma C.2, we need a purely geometric statement which we now present as a separate lemma.

Lemma C.6 *Let (M, g) be a Riemannian manifold whose sectional curvatures are uniformly bounded in absolute value by a constant $\kappa > 0$. Let r be any positive real number which satisfies*

$$0 < r \leq \min \left\{ \frac{1}{4} r_{\text{inj}}(M), \frac{1}{4} \varpi_{\kappa} \right\}.$$

Then for any points $p, q \in M$ with $|pq| < r$ there exists a geodesic ball $B = B_{r/4}(z) \subseteq M$ for some $z \in M$ satisfying $|pz| = r/2$ such that

$$|qx| \geq |px| + \frac{1}{\pi} |pq| \quad \text{for every } x \in B.$$

Proof of Lemma C.6

Consider the geodesic moving from p in the opposite direction from p to q and reaching a point in distance $r/2$. Let us denote this point by z . In our notations, we write

$$z = \exp_p \left(-\frac{r}{2} \cdot \frac{\hat{q}}{\|\hat{q}\|} \right).$$

Here we recall that $\hat{q} \in T_p M$ is the unique tangent vector with $\|\hat{q}\| < r$ such that $\exp_p(\hat{q}) = q \in M$. With $r/2 < r_{\text{inj}}(M)$, we know that this geodesic segment between p and z is

minimizing: $|pz| = r/2$. Now consider the geodesic ball of radius $r/4$ centered at z and an arbitrary point

$$x \in B_{r/4}(z) \subseteq M.$$

Lower bound on the angle $\angle(p_x^q)$. The comparison inequality (23) from Lemma B.4 applied with the upper curvature bound gives

$$\angle(p_x^z) \leq \angle^\kappa(p_x^z).$$

Since we have

- $|pz| = r/2$,
- $|zx| < r/4$,
- $|px| \geq |pz| - |zx| > r/2 - r/4 = r/4$,
- $|px| \leq |pz| + |zx| < r/2 + r/4 = 3r/4$, and
- $r \leq \varpi_\kappa/4 = \pi/(4\sqrt{\kappa})$,

a direct model-space computation (we leave the explicit computation to Lemma B.8) yields

$$\angle^\kappa(p_x^z) \leq \frac{\pi}{3}.$$

Consequently

$$\angle(p_x^q) = \angle(p_x^q) - \angle(p_x^z) \geq \pi - \frac{\pi}{3} = \frac{2\pi}{3}.$$

Opposite-side comparison for the triangle $\triangle pqx$. By the triangle inequality, we have

$$|px| \leq |pz| + |zx| < \frac{r}{2} + \frac{r}{4} = \frac{3r}{4}.$$

Hence,

$$|px| + |pq| < \frac{3r}{4} + r \leq \varpi_\kappa,$$

where the last inequality follows from the definition of r . Consequently, the model angle $\angle^\kappa(p_x^q)$ is well-defined and Lemma B.4 gives

$$|qx| \geq \Upsilon^\kappa(\angle(p_x^q); |pq|, |px|) \geq \Upsilon^\kappa\left(\frac{2}{3}\pi; |pq|, |px|\right),$$

where the last inequality follows from the fact that $\theta \mapsto \Upsilon^\kappa(\theta; |pq|, r/2)$ is a monotone increasing on $[0, \pi]$ (see e.g. (Alexander et al., 2024, Ch. 1)), and we have shown above that $\angle(p_x^q) \geq \frac{2}{3}\pi$. Finally, a direct estimate in M_κ (see Lemma I.5) shows that

$$\Upsilon^\kappa\left(\frac{2}{3}\pi; |pq|, |px|\right) \geq |px| + \frac{1}{2} \left| \cos\left(\frac{2}{3}\pi\right) \right| |pq| = |px| + \frac{1}{4} |pq|.$$

■

Proof of Lemma C.2 The proof is similar to the proof of Lemma 3.1 in [Huang et al. \(2024\)](#), which breaks into two cases depending on $|pq|$. Recall from Proposition C.1 that

$$\frac{\langle x, x \rangle_{\text{cn}} + \langle y, y \rangle_{\text{cn}}}{2} - \langle x, y \rangle = \frac{1}{2} \int_M (\text{p}(|xz|) - \text{p}(|yz|))^2 d\mu(z),$$

so our goal is to estimate the integral from below.

Case 1: $|pq| < 4r_G$. Here we can invoke Lemma C.6 to show that there exists a ball $B = B_{r_G}(z)$ for some $z \in M$ with $|pz| = 2r_G$ such that for every $x \in B$, we have

$$||px| - |qx|| \geq \frac{1}{\pi} |pq|.$$

Following triangle inequalities, we have

$$\max\{|px|, |qx|\} < (4 + 2 + 1)r_G < r_p.$$

Hence, we have

$$|\text{p}(|px|) - \text{p}(|qx|)| \geq \frac{\ell_p}{\pi} |pq|.$$

Now we use this bound to estimate the integral

$$\int_M (\text{p}(|px|) - \text{p}(|qx|))^2 d\mu(x) \geq \int_B (\text{p}(|px|) - \text{p}(|qx|))^2 d\mu(x) \geq \mu_{\min}(r_G) \frac{\ell_p^2}{\pi^2} |pq|^2.$$

Case 2: $|pq| \geq 4r_G$. Now suppose $|pq| \geq 4r_G$. Here we consider the ball $B = B_{r_G}(p)$. For any $x \in B$, simply from triangle inequalities, we have

$$|qx| \geq |pq| - |px| \geq 4r_G - r_G = 3r_G.$$

Together with $|px| \leq r_G$, we have

$$|\text{p}(|px|) - \text{p}(|qx|)| \geq \text{p}(3r_G) - \text{p}(r_G) \geq \ell_p \cdot 2r_G.$$

Then, applying the same argument as in Case 1, we have

$$\int_M (\text{p}(|px|) - \text{p}(|qx|))^2 d\mu(x) \geq \int_B (\text{p}(|px|) - \text{p}(|qx|))^2 d\mu(x) \geq \mu_{\min}(r_G) \cdot \ell_p^2 \cdot 4r_G^2.$$

■

Appendix D. Scenario 1: Forming an approximate orthogonal basis

We introduce the first scenario in an intermediate step of the overall algorithm.

Definition D.1 For $k \in [0, d]$, and consider $k + 1$ pairs $(\rho_i)_{i \in [0, k]} \in \mathbf{V}$. For parameters $0 < \eta < \delta < r$, define

$$\mathcal{E}_\perp(r, \delta, \eta, (\rho_i)_{i \in [0, k]})$$

to be the event of $(X_{U_{\rho_i}})_{i \in [0, k]}$ that the following two conditions hold:

$$||X_{\rho_0} X_{\rho_i}| - r| \leq \delta, \quad \text{for } i \in [k], \quad \text{and} \quad ||X_{\rho_i} X_{\rho_j}| - \sqrt{2}r| \leq \delta, \quad \text{for } i, j \in [k], \quad (36)$$

The main statement of this scenario is as follows:

Proposition D.2 There exists a constant $c_{D.2} = c(d, L_p, \ell_p) > 0$ and $c'_{D.2} = c'(d, L_p, \ell_p) > 0$ such that the following holds. For any $c < c_{D.2}$, let $0 < \eta < \delta < r$ and a positive integer m satisfies the parameter configuration (19):

$$\varepsilon_m < c^2 \eta, \quad \eta = c\delta, \quad \delta = cr, \quad r \leq c r_G. \quad (37)$$

Suppose we are given $k + 1$ pairs $(\rho_i, U_{\rho_i})_{i \in [0, k]}$ with $\rho_i \subseteq U_{\rho_i} \subset \mathbf{V}$ and $|U_{\rho_i}| \geq m$ (with $k \leq d$).

Let $W \subset \mathbf{V}$ be disjoint from all U_{ρ_i} and let

$$m' := \inf_q \left| \{X_w\}_{w \in W} \cap B_{c'_{D.2} c_{C.5} \eta^2}(q) \right|$$

where the infimum is taken over all points $q \in M$ satisfying

$$||X_{\rho_0} q| - r| < 0.92\delta \quad \text{and} \quad ||X_{\rho_i} q| - \sqrt{2}r| < 0.92\delta \quad (\forall i \in [k]).$$

Then, on the event

$$\mathcal{E} := \mathcal{E}_\perp(r, \delta, \eta, (\rho_i)_{i \in [0, k]}) \cap \bigcap_{i \in [0, k]} \mathcal{E}_{\text{clu}}(\eta, U_{\rho_i}, \rho_i) \cap \bigcap_{i \in [0, k]} \mathcal{E}_{\text{navi}}(U_{\rho_i}, W),$$

the set

$$\begin{aligned} W' &:= W'(r, \delta, W, (U_{\rho_i}, \rho_i)_{i \in [k]}) \\ &= \left\{ w \in W : \begin{array}{l} p(r + 0.91\delta) \leq N_{U_{\rho_0}}(w) \leq p(r - 0.91\delta), \\ p(\sqrt{2}r + 0.91\delta) \leq N_{U_{\rho_i}}(w) \leq p(\sqrt{2}r - 0.91\delta) \quad (\forall i \in [k]) \end{array} \right\} \end{aligned} \quad (38)$$

is non-empty, and for every $w \in W'$, the following holds:

$$|B_{c_{C.5} \eta^2}(X_{w'}) \cap W'| \geq m'.$$

Remark D.3 Within the event $\mathcal{E}$, by (13) from Calibration Lemma A.6, for every $w' \in W'$ we have

$$||X_{\rho_0} X_w| - r| \leq 0.92\delta \quad \text{and} \quad ||X_{\rho_i} X_w| - \sqrt{2}r| \leq 0.92\delta,$$

provided that c is chosen sufficiently small.

Remark D.4 In view of Algorithm 1, the set W' defined in (38) is a $(c_{C.5} \eta^2, m')$ -dense set, which is capable of extracting a cluster in W' with radius η and size at least m' by Proposition C.5 by measuring common neighbor sizes.

D.1. W' is not empty.

Our goal in this subsection is to show that the set W' , defined in Proposition D.2, is non-empty. The key idea is to construct a point $y \in M$ that is approximately orthogonal to the points $X_{\rho_i} \in M$, where each X_{ρ_i} belongs to one of the clusters U_{ρ_i} . This construction is possible when r is sufficiently smaller than $\min\{r_{\text{inj}}(M), \varpi_\kappa\}$, which minimizes the effect of curvature, and when δ/r is small enough to ensure approximate orthogonality. Both conditions can be achieved by choosing a sufficiently small constant c in the parameter assumptions of (37) from Proposition D.2. We now formalize this in the following geometric lemma:

Lemma D.5 *Let $p, x_1, \dots, x_k \in M$, where $k < d$, be points in M such that*

$$||p x_i| - r| \leq \delta, \quad \text{for } i \in [k],$$

and assume $r > \delta > 0$ satisfies the parameter assumption from Proposition D.2, with a sufficiently small constant c . Then, there exists a point $y \in M$ such that

$$|p y| = r, \quad \text{and} \quad ||y x_i| - \sqrt{2}r| \leq 0.9\delta \quad \text{for } i \in [k].$$

We now apply this geometric construction to prove the non-emptiness of W' under the assumptions of Proposition D.2. The proof of Lemma D.5 is postponed to the end of this subsection.

Corollary D.6 *Under the assumptions of Proposition D.2, W' is not empty.*

Proof Let $p = X_{\rho_0}$ and $x_i = X_{\rho_i}$ for $i \in [k]$. These satisfy the assumption of Lemma D.5 by construction. Hence, there exists a point $q \in M$ such that

$$|p q| = r, \quad \text{and} \quad ||q x_i| - \sqrt{2}r| \leq 0.9\delta \quad \text{for } i \in [k].$$

This point q satisfies the geometric constraints of Proposition D.2. By assumption, this implies the existence of some $w \in W$ such that

$$|p X_w| \leq c_{\text{C.5}} \eta^2.$$

Using the triangle inequality:

$$||X_{\rho_0} X_w| - r| \leq c_{\text{C.5}} \eta^2 \quad \text{and} \quad \left| |X_{\rho_i} X_w| - \sqrt{2}r \right| \leq 0.9\delta + c_{\text{C.5}} \eta^2.$$

Under the event $\mathcal{E}_{\text{clu}}(\eta, U_{\rho_0}, \rho_0)$ and the event $\mathcal{E}_{\text{navi}}(U_{\rho_0}, W)$, the Calibration Lemma A.6 applies, yielding

$$p(r + 0.9\delta + 2\eta) \leq \mathbf{N}_{U_{\rho_0}}(w) \leq p(r - 0.9\delta - 2\eta),$$

and when c is sufficiently small, we have $2\eta < 0.01\delta$. Further, an identical argument applies to all $i \in [k]$, showing that $w \in W'$. Therefore, W' is non-empty. $\blacksquare$

Proof of Lemma D.5

Recall

$$\hat{x}_i := (\hat{x}_i)_p \in T_p M \quad \text{for } i \in [d]$$

is the unique vector (thanks to $|x_i p| < c \min\{r_{\text{inj}}(M), \varpi_\kappa\}$) such that $\exp_p(\hat{x}_i) = x_i$ and $\|\hat{x}_i\| = |p x_i|$.

Since $k < d$, there exists a vector $w \in T_p M$ orthogonal to all $\hat{x}_i$, i.e.,

$$\langle \hat{x}_i, w \rangle = 0 \quad \text{for all } i \in [k] \quad \text{and} \quad \|w\| = r.$$

We claim that

$$y = \exp_p(w)$$

is the desired point. Clearly,

$$|p y| = \|w\| = r.$$

To estimate $|y x_i|$, we note that

$$\angle(p y^{x_i}) = \arccos\left(\frac{\langle \hat{x}_i, w \rangle}{\|\hat{x}_i\| \|w\|}\right) = \arccos(0) = \frac{\pi}{2}.$$

We now apply Lemma 1.7 with $\theta = \frac{\pi}{2}$, $|p x_i| = \|\hat{x}_i\|$, and $|p y| = r$ to obtain

$$\left| |x_i y|^2 - 2r^2 \right| \leq 2\delta r + \delta^2 + 2\kappa(r + \delta)^4.$$

With the assumption that $r \leq c \min\{r_{\text{inj}}(M), \varpi_{\kappa_1}\}$ and $\delta = cr$, we have

$$2\kappa(r + \delta)^4 = 2\kappa(1 + c)^4 r^4 \leq 2(1 + c)^4 c^2 r^2 \leq 2(1 + c)^4 \delta^2 \leq 3\delta^2.$$

Thus,

$$2\delta r + \delta^2 + 2\kappa(r + \delta)^4 \leq \delta r(2 + 3c) \leq 3cr^2.$$

We can first conclude that

$$|x_i y| \geq \sqrt{2r^2 - 3cr^2} = \sqrt{2 - 3c}r,$$

and consequently,

$$\left| |x_i y| - \sqrt{2}r \right| = \frac{\left| |x_i y|^2 - 2r^2 \right|}{\left| |x_i y| + \sqrt{2}r \right|} \leq \frac{\delta r(2 + 3c)}{\sqrt{2 - 3c}r + \sqrt{2}r} \leq 0.9\delta,$$

where the last inequality holds when c is sufficiently small. ■

D.2. Proof of Proposition D.2

Having established that W' is non-empty, we now aim to show that for every $w' \in W'$, there exists a ball of radius η centered at $X_{w'}$ such that

$$|B_\eta(X_{w'}) \cap W| \geq m'.$$

Intuitively, W' corresponds to the subset of latent points in W that lie near the intersection of $k + 1$ fuzzy annuli — “fuzzy” in the sense that membership is defined via edge constraints to cluster cores rather than precise metric distances. The main difficulty arises when a point $X_{w'} \in W'$ is close to the boundary of this intersection, where small perturbations may break the constraints.

To address this, we consider moving slightly along a geodesic γ , starting at $X_{w'}$ in a direction $\xi \in T_{X_{w'}}M$, to reach a point $z = \gamma(s)$ for some small $s > 0$, thereby *moving away from the boundary of the intersection region*.

Strategically, the goal is to find such a direction ξ so that the resulting point z satisfies

$$B_{c_{c,5}\eta^2}(z) \cap W \subseteq W',$$

thus ensuring that a robust neighborhood of z lies entirely within W' .

For a fixed $w' \in W'$, define

$$\sigma_0 = \begin{cases} 1 & \text{if } N_{U_{\rho_0}}(w') < p(r), \\ -1 & \text{otherwise.} \end{cases}$$

We then choose $\xi \in T_{X_{w'}}M$ such that

$$\text{sign}(\langle \xi, \hat{\rho}_0 \rangle) = \sigma_0,$$

where $\hat{\rho}_0 \in T_{X_{w'}}M$ is the tangent vector satisfying $\exp_{X_{w'}}(\hat{\rho}_0) = X_{\rho_0}$. Suppose $N_{U_{\rho_0}}(w') < p(r)$, this suggests that $|X_{\rho_0} X_{w'}| > r$. In this case, setting $\sigma_0 = 1$ means choosing ξ so that $\langle \xi, \hat{\rho}_0 \rangle > 0$, which moves z toward X_{ρ_0} along the geodesic and decreases $|X_{\rho_0} z|$, bringing it closer to r . The reverse case $N_{U_{\rho_0}}(w') > p(r)$ corresponds to $\sigma_0 = -1$, so that moving in the opposite direction increases the distance toward r .

Following the same reasoning, for each $i \in [k]$ we set

$$\sigma_i = \begin{cases} 1 & \text{if } N_{U_{\rho_i}}(w') < p(\sqrt{2}r), \\ -1 & \text{otherwise.} \end{cases}$$

Next, choose $\xi' \in \text{span}(\{\tilde{\rho}_i\}_{i \in [0,k]})$ such that

$$\text{sign}(\langle \xi', \tilde{\rho}_i \rangle) = \sigma_i \quad \text{for all } i \in [0, k],$$

where

$$\tilde{\rho}_i = \frac{\hat{\rho}_i}{\|\hat{\rho}_i\|} \in T_{X_{w'}}M \quad \text{for } i \in [0, k].$$

Finally, normalize to obtain

$$\xi = \frac{\xi'}{\|\xi'\|}.$$

In other words, we have

$$\langle \xi, \tilde{\rho}_i \rangle = \frac{\sigma_i}{\|\xi'\|}.$$

We need to ensure that $\|\xi'\|$ is not too large, so that moving along the direction ξ with a small distance still produces a non-trivial change in the distance to each X_{ρ_i} .

Lemma D.7 *Under the assumptions of Proposition D.2, for any fixed $w' \in W'$, the vector ξ defined above satisfies*

$$\|\xi'\|_2 \leq \sqrt{2(k+1)}, \quad \text{and} \quad \frac{\langle \xi, \tilde{\rho}_i \rangle}{\sigma_i} \geq \frac{1}{2(k+1)}$$

provided $c_{D.2}$ is chosen sufficiently small.

Proof Let $\xi' = \sum_{i=0}^k a_i \tilde{\rho}_i$ with $a_i \in \mathbb{R}$. Then the coefficients satisfy

$$B\mathbf{a} = \boldsymbol{\sigma}, \quad B := (\langle \tilde{\rho}_i, \tilde{\rho}_j \rangle)_{i,j=0}^k, \quad \mathbf{a} := (a_i)_{i=0}^k, \quad \boldsymbol{\sigma} := (\sigma_i)_{i=0}^k.$$

In particular, $\mathbf{a} = B^{-1}\boldsymbol{\sigma}$. Hence

$$\|\xi'\|_2^2 = \left\| \sum_{i=0}^k a_i \tilde{\rho}_i \right\|_2^2 = \mathbf{a}^\top B \mathbf{a} = \boldsymbol{\sigma}^\top B^{-1} \boldsymbol{\sigma} \leq \|B^{-1}\|_{\text{op}} \|\boldsymbol{\sigma}\|_2^2 \leq \|B^{-1}\|_{\text{op}} (k+1).$$

Therefore, it suffices to show that $s_{\min}(B) \geq \frac{1}{2(k+1)}$, i.e. $\|B^{-1}\|_{\text{op}} \leq 2(k+1)$, which then yields $\|\xi'\| \leq \sqrt{2(k+1)}$.

From law of cosine to inner products. For any $\{i, j\} \in \binom{[0, k]}{2}$, consider the geodesic triangle with vertices $(X_{w'}, X_{\rho_i}, X_{\rho_j})$. Let

$$\theta_{ij} = \angle(X_{w'} X_{\rho_j}^{X_{\rho_i}}) \in [0, \pi] \quad \text{and notice that} \quad B_{ij} = \langle \tilde{\rho}_i, \tilde{\rho}_j \rangle = \cos(\theta_{ij}).$$

Now we invoke Lemma I.7, a comparison version of law of cosines, to get

$$\left| |X_{\rho_i} X_{\rho_j}|^2 - (|X_{w'} X_{\rho_i}|^2 + |X_{w'} X_{\rho_j}|^2 - 2 |X_{w'} X_{\rho_i}| |X_{w'} X_{\rho_j}| \cos \theta_{ij}) \right| \leq C \kappa (|X_{w'} X_{\rho_i}|^4 + |X_{w'} X_{\rho_j}|^4).$$

Under the event defining W' and $\mathcal{E}_\perp$, we have, for $i, j \in [k]$,

$$|X_{\rho_i} X_{\rho_j}| = \sqrt{2}r \pm \delta, \quad |X_{w'} X_{\rho_i}| = \sqrt{2}r \pm 0.92\delta,$$

and for pairs involving 0,

$$|X_{\rho_0} X_{\rho_i}| = r \pm \delta, \quad |X_{w'} X_{\rho_0}| = r \pm 0.92\delta, \quad |X_{w'} X_{\rho_i}| = \sqrt{2}r \pm 0.92\delta.$$

Plugging these into the display above and rearranging yields the following bounds.

Case 1: $i, j \in [k]$. Using $(\sqrt{2}r)^2 = 2r^2$ and collecting terms,

$$4r^2 (1 - \cos \theta_{ij}) = 2r^2 + \text{Err}_{ij},$$

where $|\text{Err}_{ij}| \leq C_1(\delta r + \kappa r^4)$. Hence

$$\left| \cos \theta_{ij} - \frac{1}{2} \right| \leq C_2 \left(\frac{\delta}{r} + \kappa r^2 \right).$$

Case 2: one of i, j equals 0. Here

$$3r^2 - 2\sqrt{2}r^2 \cos \theta_{0i} = r^2 + \text{Err}_{0i}, \quad |\text{Err}_{0i}| \leq C_3(\delta r + \kappa r^4),$$

so

$$\left| \cos \theta_{0i} - 2^{-1/2} \right| \leq C_4 \left(\frac{\delta}{r} + \kappa r^2 \right).$$

On the diagonal we have $B_{ii} = 1$ for all i .

By the parameter regime in Proposition D.2 (namely $\delta = cr$ and $r \leq c \min\{r_{\text{inj}}(M), \varpi_\kappa\}$ so that $\kappa r^2 \lesssim c^2$), there is a constant C_* such that

$$\varepsilon := C_* \left(\frac{\delta}{r} + \kappa r^2 \right) = O(c_{\text{D.2}}),$$

and consequently

$$B_{ij} = \begin{cases} 1 & (i = j), \\ \frac{1}{2} \pm \varepsilon & (i, j \in [k], i \neq j), \\ \frac{\sqrt{2}}{2} \pm \varepsilon & (\text{one of } i, j \text{ is } 0). \end{cases}$$

Equivalently, B is a small perturbation (of size ε) of the deterministic Gram matrix with entries $\{1, \frac{1}{2}, \frac{\sqrt{2}}{2}\}$, i.e. angles $\{\pi/3, \pi/4\}$ up to $O(\varepsilon)$.

Least singular value of the baseline matrix. Let $\bar{B}$ be the $(k+1) \times (k+1)$ Gram matrix with

$$\bar{B}_{ii} = 1, \quad \bar{B}_{0i} = \bar{B}_{i0} = \alpha := \frac{\sqrt{2}}{2} \quad (i \geq 1), \quad \bar{B}_{ij} = \beta := \frac{1}{2} \quad (i \neq j, i, j \geq 1).$$

We decompose $\mathbb{R}^{k+1}$ as the orthogonal sum

$$H := \text{span}\{e_0, (0, \frac{1}{\sqrt{k}}\mathbf{1})\} \quad \text{and} \quad H^\perp := \{(0, v) : \mathbf{1}^\top v = 0\}.$$

On $H^\perp$ (dimension $k-1$), $\bar{B}$ acts by multiplication with $1 - \beta = \frac{1}{2}$, so there are $k-1$ eigenvalues equal to $\frac{1}{2}$. On H , with basis $\{e_0, (0, \frac{1}{\sqrt{k}}\mathbf{1})\}$, the restriction of $\bar{B}$ is

$$D = \begin{pmatrix} 1 & \frac{\sqrt{2}}{2}\sqrt{k} \\ \frac{\sqrt{2}}{2}\sqrt{k} & \frac{k+1}{2} \end{pmatrix}.$$

This 2×2 matrix has trace $\frac{k+3}{2}$ and determinant $\frac{1}{2}$, hence its eigenvalues are

$$\lambda_\pm(D) = \frac{\frac{k+3}{2} \pm \sqrt{\left(\frac{k+3}{2}\right)^2 - 2}}{2}. \quad \Rightarrow \quad \lambda_{\min}(\bar{B}) = \lambda_-(D) = \frac{\frac{k+3}{2} - \sqrt{\left(\frac{k+3}{2}\right)^2 - 2}}{2} \geq \frac{1}{k+3}.$$

Perturbation to the actual B . The actual Gram matrix satisfies $B = \bar{B} + E$, where

$$|E_{ij}| \leq \varepsilon, \quad \varepsilon = C \left(\frac{\delta}{r} + \kappa r^2 \right) = O(c_{\mathbf{D}.2}).$$

Thus $\|E\|_{\text{op}} \lesssim k\varepsilon$, and Weyl's inequality gives

$$\sigma_{\min}(B) \geq \sigma_{\min}(\bar{B}) - \|E\|_{\text{op}} \geq \frac{1}{k+3} - C'k\varepsilon \geq \frac{1}{2(k+1)},$$

provided that $c_{\mathbf{D}.2}$ is chosen small enough. ■

Lemma D.8 *Under the assumptions of Proposition D.2 and fix $w' \in W'$. Let $\xi = \frac{\xi'}{\|\xi'\|} \in T_{X_{w'}}M$ be the unit direction chosen as in the construction above, i.e.*

$$\xi' \in \text{span}(\{\tilde{\rho}_i\}_{i \in [0,k]}) \quad \text{satisfies} \quad \langle \xi, \tilde{\rho}_i \rangle = \sigma_i \quad \text{for all } i \in [0, k],$$

with $\tilde{\rho}_i = \hat{\rho}_i / \|\hat{\rho}_i\|$ and $\exp_{X_{w'}}(\hat{\rho}_i) = X_{\rho_i}$. Set $z = \exp_{X_{w'}}(t\xi)$ for $0 < t \leq \delta$. When $c_{\mathbf{D}.2}$ is chosen sufficiently small, we have

$$\frac{\ell_{\text{p}}}{2} \frac{t}{\|\xi'\|} \leq \sigma_i \cdot \frac{1}{|U_{\rho_i}|} \sum_{v \in U_{\rho_i}} \left(\mathbb{P}(|z X_v|) - \mathbb{P}(|X_{w'} X_v|) \right) \leq 2L_{\text{p}} \frac{t}{\|\xi'\|}. \quad (39)$$

Proof Fix $w' \in W'$ and let $\xi \in T_{X_{w'}}M$ be the unit vector chosen above. For $t > 0$ small, set

$$z := \exp_{X_{w'}}(t\xi).$$

For each $i \in [0, k]$, we apply Lemma B.9 with

$$p := X_{w'}, \quad x := X_{\rho_i}, \quad q := z.$$

Verification of the conditions of Lemma B.9. We have $|pq| = |X_{w'} z| = t$ and

$$|\cos(\angle(p_x^q))| = |\langle \xi, \tilde{\rho}_i \rangle| \geq \frac{1}{2(k+1)}$$

by Lemma D.7. Moreover, by Remark D.3 we have

$$|X_{w'} X_{\rho_i}| = \begin{cases} r \pm 0.92\delta, & i = 0, \\ \sqrt{2}r \pm 0.92\delta, & i \geq 1, \end{cases}$$

and both quantities are $O(r)$. Thus, provided $t \leq \delta$ and $c_{\mathbf{D}.2}$ is chosen sufficiently small, the two conditions from Lemma B.9 are satisfied:

$$16 \frac{t}{|X_{w'} X_{\rho_i}|} \leq \frac{1}{2(k+1)} \leq |\cos(\angle(X_{w'} z_{X_{\rho_i}}))|,$$

and

$$|X_{w'} X_{\rho_i}|, \quad t < \frac{1}{8} \min\{r_{\text{inj}}(M), \varpi_{\kappa}\}.$$

Choose $x' = X_v$ for $v \in U_{\rho_i}$. Now we take x' to be any X_v with $v \in U_{\rho_i}$ in the setting of Lemma B.9.

Within the event $\mathcal{E}_{\text{clu}}(U_{\rho_i}, \rho_i)$,

$$|X_{\rho_i} X_v| \leq \eta \quad \text{for all } v \in U_{\rho_i}.$$

Since $|px| = |X_{w'} X_{\rho_i}| \geq r - 0.92\delta$ and $\eta = c_{\text{D.2}} \delta$ with $c_{\text{D.2}}$ small, we obtain

$$16 \frac{|xx'|}{|px|} \leq 16 \frac{\eta}{r - 0.92\delta} \leq 16 \frac{c_{\text{D.2}} \delta}{r - 0.92\delta} \ll \frac{1}{2(k+1)} \leq |\cos(\angle(p_x^q))|,$$

where the last inequality uses Lemma D.7. Thus the second hypothesis of Lemma B.9 is also satisfied for this choice of x' .

Consequence. Recalling $\cos(\angle(p_x^q)) = \langle \xi, \tilde{\rho}_i \rangle = \sigma_i / \|\xi'\|$, Lemma B.9 yields

$$\frac{\ell_p}{2} \frac{t}{\|\xi'\|} \leq \sigma_i \left(\mathbb{P}(|q x'|) - \mathbb{P}(|p x'|) \right) \leq 2L_p \frac{t}{\|\xi'\|}. \quad (40)$$

Averaging (40) over $v \in U_{\rho_i}$ gives

$$\frac{\ell_p}{2} \frac{t}{\|\xi'\|} \leq \sigma_i \cdot \frac{1}{|U_{\rho_i}|} \sum_{v \in U_{\rho_i}} \left(\mathbb{P}(|z X_v|) - \mathbb{P}(|X_{w'} X_v|) \right) \leq 2L_p \frac{t}{\|\xi'\|}.$$

■

Proof of Proposition D.2

Choose t so that

$$\frac{\ell_p}{2} \frac{t}{\|\xi'\|} = 2\varepsilon_m + L_p c'_{\text{D.2}} c_{\text{C.5}} \eta^2. \quad (41)$$

By (37) and $\|\xi'\| \leq \sqrt{2(k+1)} \leq \sqrt{2(d+1)}$ from Lemma D.7, we can assume this choice satisfies

$$t \leq \frac{1}{2} c_{\text{C.5}} \eta^2 \leq 0.01\delta,$$

provided that $c_{\text{D.2}}$ and $c'_{\text{D.2}}$ are sufficiently small. In particular, it is admissible in Lemma D.8.

Let z be the point from Lemma D.8 corresponding to this t . And by Lemma D.8, It is rather straightforward to see that z satisfies the conditions in Proposition D.2:

$$||X_{\rho_0} z| - r| < 0.92\delta \quad \text{and} \quad ||X_{\rho_i} z| - \sqrt{2}r| < 0.92\delta \quad (\forall i \in [k]),$$

since $X_{w'}$ satisfies the same conditions with 0.92δ replaced by 0.91δ and $|X_{w'} z| = t \leq 0.01\delta$.

Take any $w \in W$ with

$$|z X_w| \leq c'_{\text{D.2}} c_{\text{C.5}} \eta^2,$$

whose existence is guaranteed by the definition of W .

Example case $i = 0$ and $\sigma_0 = 1$. From $\mathcal{E}_{\text{navi}}(U_{\rho_0}, w) \supseteq \mathcal{E}_{\text{navi}}(U_{\rho_0}, W)$, we have

$$\mathbb{N}_{U_{\rho_0}}(w) \geq \mathbb{P}_{U_{\rho_0}}(w) - \varepsilon_m \geq \frac{1}{|U_{\rho_0}|} \sum_{v \in U_{\rho_0}} \mathbb{P}(|z X_v|) - L_p |z X_w| - \varepsilon_m.$$

Then, invoke Lemma D.8 with $i = 0$ and $\sigma_0 = 1$ to get

$$(*) \geq \mathbf{p}_{U_{\rho_0}}(w') + \frac{\ell_p}{2} \frac{t}{\|\xi'\|} - L_p |z X_w| - \varepsilon_m \geq \mathbf{p}_{U_{\rho_0}}(w') + \varepsilon_m \geq \mathbf{N}_{U_{\rho_0}}(w') \geq p(r + 0.91\delta),$$

where the second last inequality uses the definition of W' . For the bound on the other side, notice $\sigma_0 = 1$ also implies $\mathbf{N}_{U_{\rho_0}}(w') < p(r)$, the analogous application of Lemma D.8 to the upper bound yields

$$\mathbf{N}_{U_{\rho_0}}(w) \leq \mathbf{N}_{U_{\rho_0}}(w') + 2L_p \frac{t}{\|\xi'\|} + L_p |z X_w| + \varepsilon_m \leq p(r) + 0.1\delta$$

when $c_{C.5}$ is sufficiently small.

Conclusion. We have shown that for $i = 0$ and $\sigma_0 = 1$, w satisfies the U_{ρ_0} constraints in the definition of W' . The same argument works verbatim for all $i \in [0, k]$ and both signs of σ_i . Hence

$$B_{c'_{D.2}c_{C.5}\eta^2}(z) \cap W \subseteq W'.$$

Moreover, $|z X_w| \leq t + c'_{D.2}c_{C.5}\eta^2 \leq c_{C.5}\eta^2$, so

$$|B_{c_{C.5}\eta^2}(z) \cap W'| \geq |B_{c'_{D.2}c_{C.5}\eta^2}(z) \cap W| \geq m'.$$

■

Appendix E. Scenario 2: Point Navigation via Approximate Orthogonal Basis

This is a continuation of the previous scenario, where we will focus on point navigation once we established the approximate orthogonal basis. The main result of this section is the following proposition

Proposition E.1 *There exists a constant $c_{E.1} = c(d, L_p, \ell_p) > 0$ such that the following holds. Suppose $0 < c < c_{E.1}$, $0 < \eta < \delta < r$ and a positive integer m satisfies the parameter configuration (19):*

$$\varepsilon_m := \frac{\log n}{\sqrt{s_n m}} < c\eta^2, \quad \eta = c\delta, \quad \delta = cr, \quad r \leq c \min\{r_{\text{inj}}(M), \varpi_\kappa, r_p\}. \quad (42)$$

Suppose we are given $d + 1$ pairs $\mathbf{F} = (\rho_i, U_{\rho_i})_{i \in [0, d]}$ with $\rho_i \subseteq U_{\rho_i} \subseteq \mathbf{V}$ and $|U_{\rho_i}| \geq m$. Further, let $w_1, w_2 \in \mathbf{V}$ are two vertices disjoint from U_{ρ_i} for all $i \in [0, d]$. Let

$$\psi_{\mathbf{F}}(w_1, w_2) := \sqrt{\sum_{i \in [d]} (\mathbf{N}_{U_{\rho_i}}(w_2) - \mathbf{N}_{U_{\rho_i}}(w_1))^2}.$$

Then, on the event

$$\mathcal{E} := \mathcal{E}_\perp(r, \delta, \eta, (\rho_i)_{i \in [0, d]}) \cap \bigcap_{i \in [0, d]} \mathcal{E}_{\text{clu}}(\eta, U_{\rho_i}, \rho_i) \cap \bigcap_{i \in [0, d]} \mathcal{E}_{\text{navi}}(U_{\rho_i}, \{w_1, w_2\}),$$

the following implication holds:

$$\begin{aligned} & \max\{\mathbf{N}_{U_{\rho_0}}(w_1), \mathbf{N}_{U_{\rho_0}}(w_2)\} \geq p(9\delta) \\ \Rightarrow & \frac{1}{3} L_p^{-1}(\psi_{\mathbf{F}}(w_1, w_2) - 2\sqrt{d}\varepsilon_m) \leq |X_{w_1} X_{w_2}| \leq 3 \ell_p^{-1}(\psi_{\mathbf{F}}(w_1, w_2) + 2\sqrt{d}\varepsilon_m). \end{aligned}$$

In other words, if we have two vertices w_1 and w_2 whose latent distances are sufficiently close to X_{ρ_0} , then we can estimate their latent distance using $(\mathbf{N}_{U_{\rho_i}}(w_j))_{i \in [0, k], j \in [1, 2]}$ with a high precision.

Lemma E.2 *Let $0 < \delta < r$ satisfy the same condition as in Proposition E.1. Suppose $p, x_0, x_1, \dots, x_d \in M$ satisfy*

$$||x_0 x_i| - r| \leq \delta, \quad ||x_i x_j| - \sqrt{2}r| \leq \delta \quad \forall i \neq j \in [d], \quad |p x_0| \leq 10\delta.$$

Let

$$\hat{x}_i = (\hat{x}_i)_p, \quad \mathbf{y}_i := \frac{\hat{x}_i}{\|\hat{x}_i\|} \in T_p M, \quad i \in [d],$$

and define the Gram matrix

$$A = (a_{ij})_{i, j \in [d]} = (\langle \mathbf{y}_i, \mathbf{y}_j \rangle_p)_{i, j \in [d]}.$$

Then

$$\|A - I_d\| \leq Cd \left(\frac{\delta}{r} + \kappa r^2 \right),$$

for some universal constant $C > 0$.

Proof To present the proof without focus on the computation, we will use C, C', C'' to denote universal constants that may change from line to line.

Off-diagonal entries. For $i \neq j$, by definition

$$\langle \mathbf{y}_i, \mathbf{y}_j \rangle_p = \cos(\angle(p_{x_i}^{x_j})).$$

By triangle inequality, we know that

$$||p x_i| - r| \leq |p x_0| + ||x_0 x_i| - r| \leq 10\delta + \delta \leq 11\delta.$$

Applying Lemma I.7 to the triangle $\triangle p x_i x_j$ gives

$$\left| \cos(\angle(p_{x_i}^{x_j})) - \frac{|p x_i|^2 + |p x_j|^2 - |x_i x_j|^2}{2 |p x_i| |p x_j|} \right| \leq \frac{\kappa (r + 11\delta)^4}{(r - 11\delta)^2} \leq 2 \kappa r^2.$$

From the distance assumptions,

$$\left| |p x_i|^2 + |p x_j|^2 - |x_i x_j|^2 \right| \leq C \delta r.$$

Then,

$$\left| \frac{|p x_i|^2 + |p x_j|^2 - |x_i x_j|^2}{2 |p x_i| |p x_j|} \right| \leq \frac{C \delta r}{2(r - 11\delta)^2} \leq C' \frac{\delta}{r}.$$

Combining with the curvature error term above yields

$$|\langle \mathbf{y}_i, \mathbf{y}_j \rangle_p| \leq C'' \left(\frac{\delta}{r} + 2\kappa r^2 \right), \quad i \neq j,$$

Diagonal entries. By construction $\|\mathbf{y}_i\|_p = 1$, so $a_{ii} = 1$ for all i .

Norm bound. The off-diagonal bound gives

$$\|A - I_d\| \leq \|A - I_d\|_{\text{HS}} \leq C'' d \left(\frac{\delta}{r} + \kappa r^2 \right),$$

as claimed. ■

Corollary E.3 *Under the assumptions of Lemma E.2, the vectors $\{\mathbf{y}_i\}_{i=1}^d$ form a basis of $T_p M$ and, for all $\mathbf{q} \in T_p M$,*

$$(1 - \varepsilon) \sum_{i=1}^d \langle \mathbf{y}_i, \mathbf{q} \rangle_p^2 \leq \|\mathbf{q}\|^2 \leq (1 + \varepsilon) \sum_{i=1}^d \langle \mathbf{y}_i, \mathbf{q} \rangle_p^2,$$

where $\varepsilon := 2Cd \left(\frac{\delta}{r} + \kappa r^2 \right) = \Theta(c_{\text{E.1}})$.

Proof Let A be the Gram matrix from Lemma E.2. That lemma gives

$$\|A - I_d\| \leq Cd \left(\frac{\delta}{r} + \kappa r^2 \right) := \alpha \lesssim dc_{\text{E.1}}.$$

When $c_{\text{E.1}}$ is chosen small enough, we have A is positive definite and $\{\mathbf{y}_i\}$ is a basis. For $\mathbf{q} = \sum_i q^i \mathbf{y}_i$ we have $\|\mathbf{q}\|^2 = \mathbf{q}^\top A \mathbf{q}$ and $\sum_i \langle \mathbf{y}_i, \mathbf{q} \rangle_p^2 = \mathbf{q}^\top \mathbf{q}$. The bound on $\|A - I_d\|$ implies $\|A^{-1} - I_d\| \leq \frac{\alpha}{1-\alpha} \leq 2\alpha$, hence

$$|(\mathbf{q}^\top \mathbf{q}) - (\mathbf{q}^\top A^{-1} \mathbf{q})| \leq 2\alpha \|\mathbf{q}\|^2,$$

which is exactly the stated inequality with $\varepsilon = 2\alpha$. ■

Proof of Proposition E.1 Define

$$\mathbf{b} = (b_i)_{i \in [d]} := \left(\textcolor{blue}{p}_{U_{\rho_i}}(w_2) - \textcolor{blue}{p}_{U_{\rho_i}}(w_1) \right)_{i \in [d]}.$$

We **claim** that

$$\frac{1}{\sqrt{5}} L_p^{-1} \|\mathbf{b}\|_2 \leq |X_{w_1} X_{w_2}| \leq \sqrt{5} \ell_p^{-1} \|\mathbf{b}\|_2 \quad (43)$$

Once the claim is established, we can simply compare $\psi_{\mathbf{F}}(w_1, w_2)$ and $\|\mathbf{b}\|_2$.

Let us fix an instance of $X_{U_{\rho_i}} = x_{U_{\rho_i}}$ for $i \in [0, d]$, $X_{w_j} = x_{w_j}$ for $j \in \{1, 2\}$, and $\mathcal{U}_{U_{\rho_i}, \{w_1, w_2\}} = \mathbf{u}_{U_{\rho_i}, \{w_1, w_2\}}$ such that the events described in Proposition E.1 holds. We want to apply Corollary E.3 with

$$p = x_{w_1}, \quad q = x_{w_2}, \quad x_i = x_{\rho_i} \quad \forall i \in [0, d].$$

From edge count to distance. By the Calibration Lemma A.6,

$$\mathbf{p}(|x_{w_j} x_0|) \geq \mathbf{N}_{U_{\rho_0}}(w_j) - 2\eta \geq \mathbf{p}(9\delta) - 2\eta \geq \mathbf{p}(10\delta),$$

where the last inequality holds when $c_{\mathbf{E}.1}$ is chosen small enough. Consequently, we have $|x_{w_1} x_0| \leq 10\delta$, which satisfies the assumptions of Lemma E.2 (and its Corollary E.3). Now let us write $p = x_{w_1}$, $q = x_{w_2}$ and $x_i = x_{\rho_i}$.

Notation in $T_p M$. For each $i \in [d]$ and $v \in U_{\rho_i}$, let

$$\hat{x}_i := (\hat{x}_i)_p, \quad \hat{x}_v := (\hat{x}_v)_p \text{ for } v \in U_{\rho_i}, \quad \hat{q} := (\hat{x}_{w_2})_p.$$

Define unit directions

$$\mathbf{y}_i := \frac{\hat{x}_i}{\|\hat{x}_i\|}, \quad \mathbf{y}_i^v := \frac{\hat{x}_v}{\|\hat{x}_v\|} \quad (v \in U_{\rho_i}),$$

and set

$$t_i := \langle \mathbf{y}_i, \hat{q} \rangle_p = \|\hat{q}\| \cos(\angle(p_{x_i}^q)), \quad \mathbf{t} := (t_i)_{i \in [d]}.$$

Equivalence between $\|\mathbf{t}\|_2^2$ and $\|\hat{q}\|^2$. By Corollary E.3,

$$\left(1 - \varepsilon_{\mathbf{E}.3}\right) \sum_{i=1}^d t_i^2 \leq \|\hat{q}\|^2 \leq \left(1 + \varepsilon_{\mathbf{E}.3}\right) \sum_{i=1}^d t_i^2, \quad (44)$$

where $\varepsilon_{\mathbf{E}.3} = \Theta(c_{\mathbf{E}.1})$.

Split indices by angle. Let

$$I := \left\{ i \in [d] : |\cos(\angle(p_{x_i}^q))| \geq \frac{1}{10\sqrt{d}} \right\}.$$

Then

$$\sum_{i \notin I} t_i^2 = \|\hat{q}\|^2 \sum_{i \notin I} \cos^2(\angle(p_{x_i}^q)) \leq d \cdot \frac{1}{100d} \|\hat{q}\|^2 = \frac{1}{100} \|\hat{q}\|^2,$$

and together with (44) this yields

$$\frac{1}{2} \sum_{i \in I} t_i^2 \leq \|\hat{q}\|^2 \leq 2 \sum_{i \in I} t_i^2, \quad (45)$$

provided that $c_{\mathbf{E}.1}$ is sufficiently small.

Relating b_i to t_i for $i \in I$. Fix $i \in I$. Because $|\cos(\angle(p_{x_i}^q))| \geq \frac{1}{10\sqrt{d}}$, and for all $v \in U_{\rho_i}$ we have $|x_i x_v| \leq \eta$ and $|p x_i| \asymp r$, the hypotheses of Lemma B.9 (with $p, q, x = x_i, x' = x_v$) are satisfied. Using its second conclusion,

$$\frac{\ell_p}{2} \leq \frac{\mathbf{p}(|q x_v|) - \mathbf{p}(|p x_v|)}{\cos(\angle(p_{x_i}^q)) |p q|} \leq 2L_p.$$

Averaging over $v \in U_{\rho_i}$ and recalling $t_i = \cos(\angle(p_{x_i}^q)) |pq|$,

$$\frac{\ell_p}{2} |t_i| \leq |b_i| \leq 2L_p |t_i|, \quad i \in I. \quad (46)$$

Summing (46) over $i \in I$ and combining with (45),

$$\frac{1}{4} L_p^{-2} \sum_{i \in I} b_i^2 \leq \|\hat{q}\|^2 \leq 4 \ell_p^{-2} \sum_{i \in I} b_i^2. \quad (47)$$

Bounding the complement $i \notin I$. Fix $i \notin I$ and $v \in U_{\rho_i}$. Applying Corollary I.4 to the triangle Δpqx_v , obtaining

$$\begin{aligned} |px_v| - |qx_v| &\leq |\cos(\angle(p_{x_v}^q))| \cdot |pq| + 4 \frac{|pq|^2}{|px_v|} \\ &\leq (|\cos(\angle(p_{x_v}^q))| + \angle(p_{x_v}^{x_i})) \cdot |pq| + 4 \frac{|pq|^2}{|px_v|} \end{aligned}$$

Using triangle comparison from Lemma B.4, and then Lemma B.8 yields

$$\angle(p_{x_v}^{x_i}) \leq \angle^\kappa(p_{x_v}^{x_i}) \leq 2 \frac{|x_i x_v|}{|px_i|}.$$

Together with $|\cos(\angle(p_{x_i}^q))| \leq \frac{1}{10\sqrt{d}}$,

$$|px_v| - |qx_v| \leq \left(|\cos(\angle(p_{x_i}^q))| + 2 \frac{|x_i x_v|}{|px_i|} + 4 \frac{|pq|}{|px_v|} \right) |pq| \leq \left(\frac{1}{10\sqrt{d}} + \Theta(c_{\mathbf{E}.1}) \right) |pq| \leq \frac{1}{5\sqrt{d}} |pq|,$$

under the small $c_{\mathbf{E}.1}$ assumption (using $|x_i x_v| \leq \eta$, $|px_i| \gtrsim r$, and $|pq| \leq \delta$). By Lipschitzness of p ,

$$|p(|qx_v|) - p(|px_v|)| \leq L_p \frac{1}{5\sqrt{d}} \|\hat{q}\|.$$

Averaging over $v \in U_{\rho_i}$ gives

$$|b_i| \leq L_p \frac{1}{5\sqrt{d}} \|\hat{q}\|, \quad i \notin I, \quad \Rightarrow \quad \sum_{i \notin I} b_i^2 \leq \frac{L_p^2}{25} \|\hat{q}\|^2. \quad (48)$$

Assembling the bounds for the claim. From (47) and (48),

$$\|\hat{q}\|^2 \geq \frac{1}{4} L_p^{-2} \sum_{i \in I} b_i^2 \geq \frac{1}{4} L_p^{-2} \left(\sum_{i=1}^d b_i^2 - \frac{L_p^2}{25} \|\hat{q}\|^2 \right).$$

Rearranging,

$$\left(1 + \frac{1}{100} \right) \|\hat{q}\|^2 \geq \frac{1}{4} L_p^{-2} \sum_{i=1}^d b_i^2 \quad \Rightarrow \quad \|\hat{q}\|^2 \geq \frac{1}{5} L_p^{-2} \sum_{i=1}^d b_i^2.$$

The upper bound follows from (47) and $\sum_{i \in I} b_i^2 \leq \sum_{i=1}^d b_i^2$: $\|\hat{q}\|^2 \leq 4\ell_p^{-2} \sum_{i=1}^d b_i^2$. Therefore, the claim holds.

Comparing $\sqrt{\sum_{i \in [d]} b_i^2}$. Within the event $\mathcal{E}_{\text{navi}}(U_{\rho_i}, w_j)$, we have

$$|b_i - \underbrace{(\mathbf{N}_{U_{\rho_i}}(w_2) - \mathbf{N}_{U_{\rho_i}}(w_1))}_{:=a_i}| \leq 2\varepsilon_m,$$

Viewing $\mathbf{b} = (b_i)_{i \in [d]}$ and $\mathbf{a} = (a_i)_{i \in [d]}$ as vectors in $\mathbb{R}^d$, the standard triangle inequality gives

$$||\mathbf{b}\|_2 - \|\mathbf{a}\|_2| \leq 2\sqrt{d}\varepsilon_m \quad \Leftrightarrow \quad ||\mathbf{b}\|_2 - \psi_{\mathbf{F}}(w_1, w_2)| \leq 2\sqrt{d}\varepsilon_m.$$

■

Algorithm 2: cluster-net

Input : $V_{\text{cn}}, V_{\text{net}}, V_{\text{ortho}} \subseteq \mathbf{V}$ with $V_{\text{net}} \cap V_{\text{ortho}} = \emptyset$, $|V_{\text{net}}| = |V_{\text{ortho}}| = n$.
 Parameters r, δ, η coupled by the standing choice with $c_{\text{F.1}}$.
 Integers m, s_{max} (minimum cluster size; max # orthogonal clusters to extract).
Output: Clusters $\{(U_i, u_i)\}_{i \in [k]} \subseteq V_{\text{net}}$ (a 2δ -net).
 Clusters $\{(V_j, v_j)\}_{j \in [s]} \subseteq V_{\text{ortho}}$.
 Maps $\mathbf{ax}_i : [d] \rightarrow [\ell]$ for $i \in [k]$ (orthogonal frames).
Initialization: $t \leftarrow 1$; $k \leftarrow 1$; $\ell \leftarrow 1$; $(U_1, u_1) \leftarrow \text{Algorithm 1}(V_{\text{cn}}, V_{\text{net}}, \eta)$;

```

while true do
    t ← t + 1;
    if axk is not defined for all s ∈ [d] then
        s ← the smallest index such that axk(s) is not defined. Define the candidate set

        
$$\mathcal{J}_{k,s} := \left\{ j \in [\ell] : \begin{array}{l} p(r + 0.93\delta) \leq n(u_k, v_j) \leq p(r - 0.93\delta), \\ p(\sqrt{2}r + 0.93\delta) \leq n(v_{\mathbf{ax}_k(\alpha)}, v_j) \leq p(\sqrt{2}r - 0.93\delta) \quad \forall \alpha \in [s-1] \end{array} \right\}.$$


        if Jk,s ≠ ∅ then
            | pick any j* ∈ Jk,s; set axk(s) ← j*;
        end
    else
        Define
        
$$W_{k,s} = W'(r, \delta; V_{\text{ortho}} \setminus L_{\preceq t-1}(U_k, u_k), (V_{\mathbf{ax}_k(1)}, v_{\mathbf{ax}_k(1)}), \dots, (V_{\mathbf{ax}_k(s-1)}, v_{\mathbf{ax}_k(s-1)})).$$

        from (38).
        (Vℓ+1, vℓ+1) ← Algorithm 1(Vcn, Wk,s, η);
        ℓ ← ℓ + 1.
    end
end
else
    Define the candidate set

    
$$\mathcal{V}_{k+1} = \left\{ (v, i_v) \in (V_{\text{net}} \setminus L_{\preceq t-1}) \times [k] : \mathbf{N}_{U_i}(v) \leq p(1.1\delta) \quad \forall i \in [k] \quad \text{and} \quad \mathbf{N}_{U_{i_v}}(v) \geq p(1.9\delta) \right\}$$


    if Vk+1 ≠ ∅ then
        pick any (u*, i*) ∈ Vk+1; uk+1 ← u*; Define

        
$$U^* := \left\{ v \in V_{\text{net}} \setminus L_{\preceq t-1} : \psi_{i^*}(u_{k+1}, v) \leq \frac{\ell_p}{6}\eta \text{ and } N_{U_{i^*}}(v) \geq p(3\delta) \right\}$$


        where

        
$$\psi_{i^*}(u_{k+1}, v) := \sqrt{\sum_{s \in [d]} (\mathbf{N}_{V_{\mathbf{ax}_{i^*}(s)}}(v) - \mathbf{N}_{V_{\mathbf{ax}_{i^*}(s)}}(u_{k+1}))^2}.$$


        (Uk+1, uk+1) ← (U*, u*);
        k ← k + 1;
    end
end
return ((Ui, ui), axi)i ∈ [k] and ((Vj, vj), j ∈ [ℓ]).
end
end
end

```

Appendix F. Stage 1: Algorithm `cluster-net` for extracting clusters nets with orthogonal frames

In this section we introduce the algorithm `cluster-net`, the goal of the algorithm is to extract which form a 2δ -net of M where each element in a net are equipped with an orthogonal frame of clusters. The main result of this section is the following:

Proposition F.1 *There exists a constant $0 < c_{F.1} \leq \min\{c_{D.2}, c_{E.1}\}$ so that the following holds. For any $0 < c_\star \leq c_{F.1}$,*

Set the parameters

$$r := c_{F.1} r_G \quad \delta = c_{F.1} r, \quad \eta = c_{F.1} \delta,$$

and

$$m := \mu_{\min}(c'_{D.2} c_{C.5} \eta^2 / 3) \frac{n}{2}.$$

Suppose V_{cn} , V_{net} , and V_{ortho} are disjoint vertex subsets of $\mathbf{V}$ with

$$|V_{\text{cn}}| = n_{\text{cn}} := \left\lceil \frac{C_{C.5}^4 \log^2(n)}{s_n^2 \eta^4} \right\rceil = \Theta(s_n^{-2} \log^2 n) \quad \text{and} \quad |V_{\text{net}}| = |V_{\text{ortho}}| = n, \quad (49)$$

Then with high probability, the algorithm `cluster-net` extracts a 2δ -net $(U_i, u_i)_{i \in [k]}$ from V_{net} and a collection of orthogonal clusters $(V_j, v_j)_{j \in [\ell]}$ from V_{ortho} , such that the following holds:

1. The set $\{u_k\}_{k \in [k]}$ form a 2δ -net of M with δ -separation:

$$\forall p \in M, \exists i \in [k] \text{ such that } |p X_{u_i}| \leq 2\delta, \quad \text{and} \quad |X_{u_i} X_{u_j}| > \delta, \forall i \neq j \in [k].$$

2. For each $i \in [k]$ and $j \in [\ell]$, the cluster (U_i, u_i) satisfies the event $\mathcal{E}_{\text{clu}}(\eta, U_i, u_i)$ with $|U_i| \geq m$ and, similarly, $\mathcal{E}_{\text{clu}}(\eta, V_j, v_j)$ hold with $|V_j| \geq m$.
3. For each $i \in [k]$, the clusters $(U_i, u_i), (V_{\text{ax}_i(1)}, v_{\text{ax}_i(1)}), \dots, (V_{\text{ax}_i(d)}, v_{\text{ax}_i(d)})$ satisfies the events

$$\mathcal{E}_\perp(r, \delta, \eta, (u_i, v_{\text{ax}_i(1)}, \dots, v_{\text{ax}_i(d)})).$$

Remark F.2 *The choice of m was arrives from Proposition D.2. And the choice of $|V_{\text{cn}}|$ is due to (33) from Proposition C.5.*

Remark F.3 *We further remark that the choice of $c_{F.1}, r, \delta, \eta$ and m satisfy the assumptions of Propositions D.2 and E.1.*

Algorithm `cluster-net` Outline The algorithm attempts to extract clusters in a sequential process. We index the steps by

$$t = 1, 2, \dots, T,$$

where for concreteness we may assume $T \leq n(d+1)$. At each step we might extract a new cluster from V_{net} or from V_{ortho} .

At the end of the process we obtain two sequences of clusters:

$$\{(U_i, u_i)\}_{i \in [k]}, \quad k \leq d, \quad U_i \subseteq V_{\text{net}},$$

and

$$\{(V_j, v_j)\}_{j \in [\ell]}, \quad V_j \subseteq V_{\text{ortho}}.$$

Cluster property. By a *cluster* (U_i, u_i) we mean that the cluster event

$$\mathcal{E}_{\text{clu}}(\eta, U_i, u_i)$$

holds; i.e., every $v \in U_i$ satisfies $|X_{u_i} X_v| \leq \eta$. Similarly, for each (V_j, v_j) we assume $\mathcal{E}_{\text{clu}}(\eta, V_j, v_j)$ holds.

Orthogonal frames. For each (U_i, u_i) we construct an index map

$$\mathbf{ax}_i : [d] \longrightarrow [\ell],$$

such that the collection

$$(U_i, u_i), (V_{\mathbf{ax}_i(1)}, v_{\mathbf{ax}_i(1)}), \dots, (V_{\mathbf{ax}_i(d)}, v_{\mathbf{ax}_i(d)}))$$

forms an *orthogonal frame of clusters*. Precisely, they satisfy the event

$$\mathcal{E}_{\perp}(r, \delta, \eta, m; (U_i, u_i), (V_{\mathbf{ax}_i(1)}, v_{\mathbf{ax}_i(1)}), \dots, (V_{\mathbf{ax}_i(d)}, v_{\mathbf{ax}_i(d)})).$$

Moreover, the set of centers $\{u_i\}_{i \in [k]}$ forms a 2δ -net of M .

Extraction times and notation. For each u_i (resp. v_j) we denote by $t(u_i)$ (resp. $t(v_j)$) the step at which it is extracted. We set

$$L_t := \begin{cases} U_i, & \text{if } t(u_i) = t, \\ V_j, & \text{if } t(v_j) = t, \\ \emptyset, & \text{if no cluster is extracted at step } t, \end{cases} \quad \ell_t := \begin{cases} u_i, & \text{if } t(u_i) = t, \\ v_j, & \text{if } t(v_j) = t. \\ \emptyset, & \text{if no cluster is extracted at step } t. \end{cases}$$

Thus (L_t, ℓ_t) is the cluster extracted at step t (when one exists). We also define the revealed sets

$$L_{\prec t} := \bigcup_{s < t} L_s, \quad L_{\preceq t} := \bigcup_{s \leq t} L_s.$$

Edge revealing process. Initially the algorithm only observes the edges connecting V_{cn} to V_{net} and V_{ortho} . Whenever at step t a cluster L_t is extracted, we reveal all edges from L_t to

$$V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq t-1}.$$

(Note that edges from L_t to $L_{\preceq t-1}$ have already been revealed when previous clusters were extracted.) This convention makes independence transparent: *The data generated up to step t does not rely on edges that have not been revealed yet, so that these data are independent*

of the edges that will be revealed in the future. In particular, whenever we reveal the edges from L_t to $V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq t-1}$, we expect the fluctuation event

$$\mathcal{E}_{\text{navi}}(L_t, V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq t-1})$$

to hold. This means that for every $v \in V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq t-1}$, if $N_{L_t}(v) \geq p(r_G)$, then $p^{-1}(N_{L_t}(v))$ estimate the distance of ℓ_t to v up to an error 2η .

Distance between centers. Given extracted cluster centers u_k, v_i, v_j , we define

$$n(u_k, v_j) := \begin{cases} N_{U_{u_k}}(v_j), & \text{if } t(u_k) < t(v_j), \\ N_{V_j}(u_k), & \text{if } t(v_j) < t(u_k). \end{cases} \quad \text{and} \quad n(v_i, v_j) := \begin{cases} N_{V_i}(v_j), & \text{if } t(v_i) < t(v_j), \\ N_{V_j}(v_i), & \text{if } t(v_j) < t(v_i). \end{cases} \quad (50)$$

That is, $n(u_k, v_j)$ is always measured using the *earlier* cluster's vertex set, so that the corresponding fluctuation event (of the form $\mathcal{E}_{\text{navi}}(L_t(\cdot), \cdot)$) was assumed, but not the later, to avoid justification of independence.

Step t of the algorithm. At step t , suppose we have extracted (U_i, u_i) for $i \in [k]$ and (V_j, v_j) for $j \in [\ell]$, where $k = k(t)$ and $\ell = \ell(t)$ are the number of clusters extracted so far from V_{net} and V_{ortho} , respectively. If $\mathbf{ax}_k$ is not defined for all $s \in [d]$. Then the goal of t -th step is to define $\mathbf{ax}_k(s)$ where s is the smallest index such that $\mathbf{ax}_k(s)$ is not yet defined:

- It first checks whether there exists a cluster (V_j, v_j) already extracted from V_{ortho} that is a valid candidate for $\mathbf{ax}_k(s)$. If so, we set $\mathbf{ax}_k(s) = j$.
- If not, then we extract a new cluster (V_ℓ, v_ℓ) from V_{ortho} and set $\mathbf{ax}_k(s) = \ell$. (This corresponds to *Scenario 1*.)

On the other hand, if $\mathbf{ax}_k$ is already defined for all $s \in [d]$, then the goal of t -th step is to extract a new cluster from V_{net} . This new cluster must be at least 2δ away from all previously extracted clusters in V_{net} , but within 3δ of some previously extracted cluster in V_{net} . (This corresponds to *Scenario 2*.)

Proof roadmap. We define a sequence of “good” events $\{\Omega(t)\}_{t \geq 0}$ adapted to the sequential extraction, where $\Omega(0)$ summarizes the initial conditions, and $\Omega(t)$ collects the desired properties after step t (e.g., cluster validity, edge fluctuation bounds on all revealed edges, and the orthogonal frame properties). Write $\Omega(\preceq t) := \bigcap_{t' \preceq t} \Omega(t')$. We first show that

$$\Pr(\Omega(0)) = 1 - n^{-\omega(1)}.$$

Inductively, assume $\Omega(\preceq t)$ holds at the beginning of step $t+1$. If the algorithm does *not* terminate at step $t+1$, we prove the one-step estimate

$$\Pr(\Omega(t+1) \mid \Omega(\preceq t)) = 1 - n^{-\omega(1)}. \quad (51)$$

If the algorithm *does* terminate at step $t+1$, then $\Omega(\preceq t)$ will imply that the output satisfies the conclusion of the proposition.

Since in each iteration we either (i) extend a frame coordinate and/or (ii) add a new net cluster, the procedure terminates after at most $T \leq n(d+1)$ steps. A union bound over the at most T exposures in (51) yields

$$\Pr(\Omega(\leq T)) \geq 1 - T \cdot n^{-\omega(1)} = 1 - n^{-\omega(1)},$$

Consequently, with probability $1 - n^{-\omega(1)}$ either the algorithm terminates early with the stated output, or it maintains $\Omega(t)$ at every step up to termination, proving the proposition.

Definition of the events $\Omega(t)$. Now let us define the events $\Omega(t)$ more precisely. First, the initial event $\Omega(0)$ is defined as follows:

$$\Omega(0) := \mathcal{E}_{\text{cn}}(V_{\text{cn}}, V_{\text{net}}) \cap \mathcal{E}_{\text{cn}}(V_{\text{cn}}, V_{\text{ortho}}) \cap \mathcal{E}_{\text{pt}}(V_{\text{net}}) \cap \mathcal{E}_{\text{pt}}(V_{\text{ortho}}).$$

As for $\Omega(t)$, it contains two components: The first event concerns about a new extracted cluster

$$\Omega_{\text{clu}}(t) := \begin{cases} \{|L_t| \geq m\} \cap \mathcal{E}_{\text{clu}}(\eta, L_t, \ell_t) \cap \mathcal{E}_{\text{navi}}(L_t, V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\leq t-1}) & \text{if } L_t \neq \emptyset, \\ \text{True} & \text{otherwise.} \end{cases} \quad (52)$$

The second event concerns the orthogonal frame property:

$$\Omega_{\perp}(t) := \begin{cases} \mathcal{E}_{\perp}(r, \delta, \eta, (u_k, v_{\text{ax}_k(1)}, \dots, v_{\text{ax}_k(s)})_{j \in [s]}) & \text{if } \text{ax}_k(s) \text{ is defined at step } t, \\ \text{True} & \text{otherwise.} \end{cases} \quad (53)$$

The third event is a net property that is only checked when the algorithm terminates:

$$\Omega_{\text{net}}(t) := \begin{cases} \left\{ \{u_i\}_{i \in [k]} \text{ is a } 2\delta\text{-net of } M \right\} & \text{if the algorithm terminates at step } t, \\ \text{True} & \text{otherwise.} \end{cases} \quad (54)$$

The $\Omega(t)$ event is then defined as the intersection of these three events:

$$\Omega(t) := \Omega_{\text{clu}}(t) \cap \Omega_{\perp}(t) \cap \Omega_{\text{net}}(t),$$

Remark on randomness and data structure. It is worth to remark that all (U_i, u_i) , (V_j, v_j) , and ax_i are all random. In particular, the revealing order matters. To analyze the algorithm, we will define $\mathcal{D}_t$ to be a set of possible data that can be generated by the algorithm up to step t :

Definition F.4 *A data set $\mathcal{D}_t$ is a collection of tuples*

$$\mathcal{D}_t = \left\{ (U_i^{\#}, u_i^{\#}, t_{u_i^{\#}})_{i \in [k^{\#}]}, \quad (V_j^{\#}, v_j^{\#}, t_{v_j^{\#}})_{j \in [\ell^{\#}]}, \quad \text{ax}_i^{\#} : [d] \rightarrow [\ell^{\#}], \quad i \in [k^{\#}-1], \text{ax}_{k^{\#}}^{\#} : [s^{\#}] \rightarrow [\ell^{\#}] \right\}.$$

Further, we say that a data set $\mathcal{D}_t$ is compatible with the Algorithm 2 at step t if

1. $k(t) = k^{\#}$ and $\ell(t) = \ell^{\#}$;
2. $(U_i, u_i) = (U_i^{\#}, u_i^{\#})$ and $t(u_i) = t_{u_i^{\#}}$ for all $i \in [k^{\#}]$;

3. $(V_j, v_j) = (V_j^\sharp, v_j^\sharp)$ and $t(v_j) = t_{v_j^\sharp}$ for all $j \in [\ell^\sharp]$.
4. $\mathbf{ax}_i = \mathbf{ax}_i^\sharp$ for all $i \in [k^\sharp - 1]$ and $\mathbf{ax}_k = \mathbf{ax}_{k^\sharp}^\sharp$ for all $i \in [s^\sharp]$. In particular, $\mathbf{ax}_k$ is only defined for $[s^\sharp]$.

Here, $k^\sharp$ and $\ell^\sharp$ indicates the number of clusters extracted from V_{net} and V_{ortho} , respectively, and $s^\sharp$ indicates the number of coordinates of the orthogonal frame that have been defined for the last extracted cluster from V_{net} . For each $i \in [k^\sharp]$ and $j \in [\ell^\sharp]$, the pair $(U_i^\sharp, u_i^\sharp)$ (resp. $(V_j^\sharp, v_j^\sharp)$) is a cluster extracted from V_{net} (resp. V_{ortho}) at step $t_{u_i^\sharp}$ (resp. $t_{v_j^\sharp}$).

Basic properties. Before we proceed, let us make a few observations.

Fact F.5 *From the Algorithm 2, whenever L_t is extracted at step t , we have*

$$L_{t+1} \subseteq V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq t},$$

whenever $L_{t+1} \neq \emptyset$.

Before proceeding, we also make a remark on the running time.

Remark F.6 *First, we remark that given δ is a constant. The δ -separation set of M has size at most $O(1)$ (independent of n). Therefore, the algorithm **cluster-net** will terminate in $O(1)$ steps. In each iteration, the most time-consuming step is to run the cluster-finding algorithm (Algorithm 1) which takes time $O(n^2(\log(n) + s_n^2|V_{\text{cn}}|)) = O(n^2 \log^2 n)$. Therefore, the total running time of Algorithm 2 is $O(n^2 \log^2 n)$.*

F.1. Main Technical Lemma

This subsection is devoted to prove the following lemma.

Lemma F.7 *For each step $t \geq 0$,*

$$\Pr(\Omega(t+1) \mid \Omega(\preceq t)) = 1 - n^{-\omega(1)}.$$

First of all, if the algorithm is already terminated before or at t , then $\Omega(t+1)$ is trivially true. Therefore, we only need to consider the case that the algorithm does not terminate at step t .

A realization of partial information of the graph. From now on, we assume that the algorithm does not terminate at step t and we fix a data structure $\mathcal{D}_t$, we will first condition on the event $\Omega(\preceq t)$ and the data set $\mathcal{D}_t$. If we run the algorithm with t iterations, then the edges that have been revealed are

$$E(V_{\text{cn}}, V_{\text{net}} \cup V_{\text{ortho}}) \cup \bigcup_{\alpha \leq t} E(L_\alpha, V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq \alpha-1}),$$

which are functions of the independent random variables

$$\begin{aligned} X &:= (X_{V_{\text{cn}}}, X_{V_{\text{net}}}, X_{V_{\text{ortho}}}), & \mathcal{U}_0 &:= \{\mathcal{U}_{u,v} : u \in V_{\text{cn}}, v \in V_{\text{net}} \cup V_{\text{ortho}}\} \\ \text{and} \quad \mathcal{U}_\alpha &:= \{\mathcal{U}_{u,v} : u \in L_\alpha, v \in V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq \alpha-1}\}, & \text{for } \alpha \in [t]. \end{aligned}$$

We remark that the sets L_α are all determined by $\mathcal{D}_t$ for $\alpha \leq t$. At the same time, $\Omega(\preceq t)$ is an event of $X, \mathcal{U}_0, \mathcal{U}_1, \dots, \mathcal{U}_t$. Now, let us *fix* a realization

$$X = x \quad \text{and} \quad \mathcal{U}_{[0,t]} = \mathcal{U}_{[0,t]}^\sharp,$$

of the random variables so that it is within the event $\Omega(\preceq t)$, and with this realization, the data set generated by the algorithm up to step t is exactly $\mathcal{D}_t$.

From the data set $\mathcal{D}_t$, we can determine what's the goal of the algorithm at step $t+1$. There are two cases: either the algorithm tries to define $\mathbf{ax}_k(s)$ for some $s \in [d]$, which may involve extracting a new cluster from V_{ortho} , or it tries to extract a new cluster from V_{net} . Let us consider it case by case by following the structure of the algorithm.

Special case: $t = 0$. At the first iteration, we simply generate the first cluster (U_1, u_1) by

$$(U_1, u_1) = \text{Algorithm 1}(V_{\text{net}}, V_{\text{ortho}}, \eta).$$

In this case,

$$\Omega(1) = \Omega_{\text{clu}}(1).$$

From $\mathcal{E}_{\text{pt}}(V_{\text{net}}) \supseteq \Omega(0)$, we know that for every $q \in M$,

$$|B_{c_{C.5\eta^2}}(q) \cap \{X_v\}_{v \in V_{\text{net}}}| \geq m.$$

Together with $\mathcal{E}_{\text{cn}}(V_{\text{cn}}, V_{\text{net}}) \supseteq \Omega(0)$, we can apply Proposition C.5 to conclude that with probability $1 - n^{-\omega(1)}$, the event $\mathcal{E}_{\text{clu}}(\eta, U_1, u_1)$ holds with $|U_1| \geq m$.

So it remains to check the event $\mathcal{E}_{\text{navi}}(L_1, V_{\text{net}} \cup V_{\text{ortho}} \setminus L_1)$ where $L_1 = U_1$. Given that all the edges from L_1 to $V_{\text{net}} \cup V_{\text{ortho}} \setminus L_1$ have not been revealed yet, we simply apply Lemma A.2, which gives

$$\Pr(\mathcal{E}_{\text{navi}}(L_1, V_{\text{net}} \cup V_{\text{ortho}} \setminus L_1) \mid X = x, \mathcal{U}_{[0,t]} = \mathcal{U}_{[0,t]}^\sharp) = 1 - n^{-\omega(1)}.$$

Since this probability estimate is true for any realization $X = x$ and $\mathcal{U}_{[0,t]} = \mathcal{U}_{[0,t]}^\sharp$ within the event $\Omega(\preceq t)$, and also every data set $\mathcal{D}_t$ compatible with the algorithm at step t and $\Omega(0)$, we have

$$\Pr(\Omega(1) \mid \Omega(0)) = 1 - n^{-\omega(1)}.$$

This concludes the proof of the case $t = 0$. From now on, we assume $t \geq 1$.

Case 1: $\mathbf{ax}_k$ is not defined for all $s \in [d]$. In this case, the algorithm tries to define $\mathbf{ax}_k(s)$ where s is the smallest index such that $\mathbf{ax}_k(s)$ is not yet defined. The candidate set

$$\mathcal{J}_{k,s} := \left\{ j \in [\ell] : \begin{array}{l} p(r + 0.93\delta) \leq n(u_k, v_j) \leq p(r - 0.93\delta), \\ p(\sqrt{2}r + 0.93\delta) \leq n(v_{\mathbf{ax}_k(\alpha)}, v_j) \leq p(\sqrt{2}r - 0.93\delta) \quad \forall \alpha \in [s-1] \end{array} \right\}$$

is then constructed in the algorithm.

Case 1.1: $\mathcal{J}_{k,s} \neq \emptyset$. First, the event $\Omega_{\text{clu}}(t+1)$ is trivially true since no new cluster will be extracted. Now one needs to verify the event

$$\Omega_\perp(t) = \mathcal{E}_\perp(r, \delta, \eta, (u_k, v_{f_1(1)}, \dots, v_{\mathbf{ax}_k(s-1)}, v_{\mathbf{ax}_k(s)})).$$

To see this, we first remark that

$$\mathcal{E}_\perp(r, \delta, \eta, (u_k, v_{f_1(1)}, \dots, v_{\mathbf{ax}_k(s-1)})) \supseteq \Omega(\preceq t)$$

It remains to verify that

$$|X_{u_k} X_{v_{\mathbf{ax}_k(s)}}| - r \leq \delta \quad \text{and} \quad |X_{v_{\mathbf{ax}_k(\alpha)}} X_{v_{\mathbf{ax}_k(s)}}| - \sqrt{2}r \leq \delta \quad \text{for } \alpha \in [s-1],$$

which follows directly from the definition of $\mathcal{J}_{k,s}$ and (13) in Calibration Lemma A.6 provided that $c_{\mathbf{F}.1}$ is sufficiently small. In other words,

$$\mathbb{P}\left(\Omega(t+1) \mid \mathcal{J}_{k,s} \neq \emptyset, X = x, \mathcal{U}_{[0,t]} = \mathcal{U}_{[0,t]}^\sharp\right) = 1.$$

Case 1.2: $\mathbf{ax}_k(s)$ is defined by extracting a new cluster $(V_{\ell+1}, v_{\ell+1})$ from V_{ortho} . In this case, (13) in Calibration Lemma A.6, we know that for every $j \in [\ell] \setminus \{\mathbf{ax}_k(1), \dots, \mathbf{ax}_k(s-1)\}$, and any vertex $v' \in V_j$ DOES NOT satisfies one of the following condition

$$|X_{u_k} X_{v'}| - r \leq 0.928\delta \quad \text{or} \quad |X_{v_{\mathbf{ax}_k(\alpha)}} X_{v'}| - \sqrt{2}r \leq 0.928\delta \quad \text{for some } \alpha \in [s-1],$$

provided that $c_{\mathbf{F}.1}$ is sufficiently small. Further, the above property also holds for $v' \in V_{\mathbf{ax}_k(\alpha)}$ for every $\alpha \in [s-1]$, since it clearly violates the second condition. Therefore, for any $q \in M$ such that

$$|X_{u_k} q| \in [r - 0.92\delta, r + 0.92\delta] \quad \text{and} \quad |X_{v_{\mathbf{ax}_k(\alpha)}} q| \in [\sqrt{2}r - 0.92\delta, \sqrt{2}r + 0.92\delta] \quad \text{for } \alpha \in [s-1],$$

every $q' \in B_{c_{\mathbf{D}.2}\eta^2}(q)$ satisfies the above inequality with 0.92 replaced by 0.921, by triangle inequalities. Hence, we conclude that

$$(V_{\text{ortho}} \setminus L(\preceq t)) \cap B_{c_{\mathbf{D}.2}\eta^2}(q) = V_{\text{ortho}} \cap B_{c_{\mathbf{D}.2}\eta^2}(q),$$

which in term implies that

$$\left| (V_{\text{ortho}} \setminus L(\preceq t)) \cap B_{c_{\mathbf{D}.2}\eta^2}(q) \right| \geq m,$$

from $\mathcal{E}_{\text{pt}}(V_{\text{ortho}}) \supseteq \Omega(0)$ and our choice of m . In particular, the condition in Proposition D.2 is satisfied with $m = m'$, and so does the event $\mathcal{E}_\perp(r, \delta, \eta, (u_k, v_{\mathbf{ax}_k(1)}, \dots, v_{f_k(s-1)}))$. Therefore, by Proposition D.2, Proposition C.5, and Remark D.3, the output $(L_{t+1}, \ell_{t+1}) = (V_{\ell+1}, v_{\ell+1})$ of the subalgorithm Algorithm 1(V_{cn}, W', η) satisfies the event $\mathcal{E}_{\text{clu}}(\eta, V_{\ell+1}, v_{\ell+1})$ with $|V_{\ell+1}| \geq m$ and

$$\mathcal{E}_\perp(r, \delta, \eta, (u_k, v_{\mathbf{ax}_k(1)}, \dots, v_{f_k(s-1)}, v_{\ell+1})).$$

In particular, all events in the definition of $\Omega_{\text{clu}}(t+1)$ and $\Omega_\perp(t+1)$ hold with the exception of the event $\mathcal{E}_{\text{navi}}(L_{t+1}, V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq t-1})$. For the latter, we note that all edges from L_{t+1} to $V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq t}$ have not been revealed yet. To be precise, the variables $\mathcal{U}_{u,v}$ for $u \in L_{t+1}$ and $v \in V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq t}$ have not been revealed yet. Therefore, by Lemma A.2, we have

$$\begin{aligned} & \mathbb{P}(\Omega(t+1) \mid \mathcal{J}_{k,s} = \emptyset, X = x, \mathcal{U}_{[0,t]} = \mathcal{U}_{[0,t]}^\sharp) \\ &= \mathbb{P}(\mathcal{E}_{\text{navi}}(L_{t+1}, V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq t}) \mid X_{L_{t+1}} = x_{L_{t+1}}, X_{V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq t}} = x_{V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq t}}) \\ &= 1 - n^{-\omega(1)}. \end{aligned}$$

Case 2: f_k is already defined for all $s \in [d]$ and the algorithm tries to extract a new cluster from V_{net} .
 In this case, the candidate set

$$\mathcal{V}_{k+1} = \left\{ (v, i_v) \in (V_{\text{net}} \setminus L_{\preceq t-1}) \times [k] : N_{U_i}(v) \leq p(1.1\delta) \quad \forall i \in [k] \quad \text{and} \quad N_{U_{i_v}}(v) \geq p(1.9\delta) \right\}$$

is defined. For each $(v, i_v) \in \mathcal{V}_{k+1}$, by $\mathcal{E}_{\text{navi}}(L_\alpha, V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\preceq \alpha-1}) \supseteq \Omega(\preceq t)$ for all $\alpha \leq t$. Then invoking the annulus calibration (13) in Calibration Lemma A.6 we have

$$|X_{u_i} X_v| \geq \delta \quad \text{for all } i \in [k], \quad \text{and} \quad |X_{u_{i_v}} X_v| \leq 2\delta,$$

provided that $c_{\text{F.1}}$ is sufficiently small.

Case 2.1: $\mathcal{V}_{k+1} \neq \emptyset$. For each $v \in U^*$, the Calibration Lemma A.6 implies that

$$|X_v X_{u_{i^*}}| \leq 3.1\delta \quad \Rightarrow \quad U^* \subseteq (V_{\text{net}} \setminus L_{\preceq t}) \cap B_{3.1\delta}(u_{i^*}).$$

where we use $B_{3.1\delta}(u_{i^*})$ to denote the set of vertices $v \in \mathbf{V}$ such that $|X_v X_{u_{i^*}}| \leq 3.1\delta$. Now, we want to apply Proposition E.1 for

$$\begin{aligned} ((U_{\rho_i}, \rho_i))_{i \in [0, d]} &= ((U_{i^*}, u_{i^*}), (V_{\text{ax}_{i^*}(1)}, v_{\text{ax}_{i^*}(1)}), \dots, (V_{\text{ax}_{i^*}(d)}, v_{\text{ax}_{i^*}(d)})) \\ w_1 &= u^* \quad \text{and} \quad w_2 \in (V_{\text{net}} \setminus L_{\preceq t}) \cap B_{3.1\delta}(u_{i^*}). \end{aligned}$$

Clearly, the assumed events in Proposition E.1 are satisfied from $\Omega(\preceq t)$. Further, we also have, for each $v \in (V_{\text{net}} \setminus L_{\preceq t}) \cap B_{4\delta}(X_{u_{i^*}})$, we have

$$p(N_{U_{i^*}}(v)) \geq p(4\delta + \eta) - \varepsilon_m \geq p(9\delta),$$

satisfying the condition in Proposition E.1. Therefore, we conclude that each $v \in U^*$ satisfies

$$|X_{u^*} X_v| \leq \frac{3}{\ell_p}(\psi_{i^*}(u^*, v) + 2\sqrt{d}\varepsilon_m) \leq \frac{3}{\ell_p}\left(\frac{\ell_p}{6}\eta + 2\sqrt{d}\varepsilon_m\right) \leq \eta,$$

provided that $c_{\text{F.1}}$ is sufficiently small. Therefore, the event

$$\mathcal{E}_{\text{clu}}(\eta, U_{k+1}, u_{k+1}) = \mathcal{E}_{\text{clu}}(\eta, U^*, u^*)$$

holds.

Next, consider

$$V_{\text{net}} \setminus L_{\preceq t} = V_{\text{net}} \setminus \left(\bigcup_{i \in [k]} U_i \right).$$

For each $u \in U_i$ for some $i \in [k]$, by the event $\mathcal{E}_{\text{clu}}(\eta, U_i, u_i) \supseteq \Omega(\preceq t)$, we have

$$|X_u X_{u^*}| \geq |X_{u_i} X_{u^*}| - |X_u X_{u_i}| \geq \delta - \eta \geq 0.9\delta.$$

Thus,

$$B_{0.9\delta}(u^*) \cap V_{\text{net}} \subseteq V_{\text{net}} \setminus L_{\preceq t}.$$

Fix any $v \in V_{\text{net}}$ such that

$$|X_v X_{u^*}| \leq \frac{\ell_p}{18L_p} \eta.$$

First, $v \in V_{\text{net}} \setminus L_{\leq t}$. Second, by triangle inequalities, we have

$$|X_v X_{u_i^*}| \leq |X_{u^*} X_{u_i^*}| + \frac{\ell_p}{18L_p} \eta \leq 2.1\delta,$$

and therefore, by the event $\mathcal{E}_{\text{navi}}(L_{i^*}, V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\leq i^*-1}) \supseteq \Omega(\leq t)$ and (13) in Calibration Lemma A.6, we have

$$p(N_{U_{i^*}}(v)) \geq p(3\delta).$$

Third, by Proposition E.1, we have

$$\psi_{i^*}(u^*, v) \leq 3L_p |X_{u^*} X_v| \leq \frac{\ell_p}{6} \eta.$$

Together we conclude that

$$B_{\ell_p \eta / 18L_p}(u^*) \cap V_{\text{net}} \subseteq U^*,$$

and therefore, by $\mathcal{E}_{\text{pt}}(V_{\text{net}}) \supseteq \Omega(0)$ and our choice of m , we have

$$|L_{t+1}| = |U^*| \geq |B_{\ell_p \eta / 18L_p}(u^*) \cap V_{\text{net}}| \geq m,$$

provided that $c_{\text{F.1}}$ is sufficiently small. Therefore, the only missing event in the definition of $\Omega_{\text{clu}}(t+1)$ and $\Omega_{\perp}(t+1)$ is the event $\mathcal{E}_{\text{navi}}(L_{t+1}, V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\leq t-1})$. As in Case 1.2, all edges from L_{t+1} to $V_{\text{net}} \cup V_{\text{ortho}} \setminus L_{\leq t}$ have not been revealed yet. Therefore, the same analysis as in Case 1.2 shows that

$$\mathbb{P}(\Omega(t+1) \mid \mathcal{V}_{k+1} \neq \emptyset, X = x, \mathcal{U}_{[0,t]} = \mathcal{U}_{[0,t]}^{\sharp}) = 1 - n^{-\omega(1)}.$$

Case 2.2: $\mathcal{V}_{k+1} = \emptyset$. Suppose there exists $v \in V_{\text{net}} \setminus L_{\leq t}$ such that

$$|X_v X_{u_i}| \geq 2\delta \quad \text{for all } i \in [k].$$

Let γ be the geodesic from X_v to X_{u_1} . Let p be the first time on γ such that $|p X_{u_i}| = 1.5\delta$ for some $i' \in [0, k]$. By the event $\mathcal{E}_{\text{pt}}(V_{\text{net}}) \supseteq \Omega(0)$, there exists $v' \in V_{\text{net}}$ such that $|X_{v'} p| \leq 0.1\delta$. Therefore, we have

$$|X_v X_{u_i}| \geq 1.4\delta \quad \text{for all } i \in [k], \quad \text{and} \quad |X_v X_{u_{i'}}| \leq 1.6\delta.$$

In particular, from the event $\mathcal{E}_{\text{clu}}(\eta, U_i, u_i) \supseteq \Omega(\leq t)$ for all $i \in [k]$, we have

$$v \in V_{\text{net}} \setminus L_{\leq t}$$

and consequently, $(v, i') \in \mathcal{V}_{k+1}$, contradicting the assumption that $\mathcal{V}_{k+1} = \emptyset$. Therefore, we conclude that when $\mathcal{V}_{k+1} = \emptyset$, there is no $p \in M$ such that

$$|p X_{u_i}| \geq 2\delta \quad \text{for all } i \in [k].$$

Therefore, the event $\Omega_{\text{net}}(\mathbf{t} + 1)$ is true.

In short, we conclude that

$$\mathbb{P}(\Omega(\mathbf{t} + 1) \mid X = x, \mathcal{U}_{[0, \mathbf{t}]} = \mathcal{U}_{[0, \mathbf{t}]}^\#)$$

for every realization x and $\mathcal{U}_{[0, \mathbf{t}]}^\#$ such that $\Omega(\preceq \mathbf{t})$ holds and $\mathcal{D}_{\mathbf{t}}$ is the data set generated by the algorithm up to step $\mathbf{t}$. Since the above holds for every such realization and $\mathcal{D}_{\mathbf{t}}$ that is compatible with $\Omega(\preceq \mathbf{t})$, we conclude that

$$\mathbb{P}(\Omega(\mathbf{t} + 1) \mid \Omega(\preceq \mathbf{t})) = 1 - n^{-\omega(1)}.$$

Proof of Proposition F.1 By the Lemma, it is clear that

$$\mathbb{P}(\Omega(\preceq (d + 1)n)) = 1 - n^{-\omega(1)}.$$

Within the event $\Omega(\preceq (d + 1)n)$, the algorithm terminates at step $\mathbf{t} \leq (d + 1)n$. This is because at each step $\mathbf{t}$, either a new cluster (U_i, u_i) from V_{net} is extracted, or a cluster (V_j, v_j) is assigned to form an orthogonal pair. There can be at most n clusters extracted from V_{net} , given the size of V_{net} , and thus the algorithm must terminate by step $(d + 1)n$. ■

Appendix G. Stage 2: Distilling fine clusters

Proposition G.1 *There exists $c_{G.1} > 0$ such that the following holds. Recall the parameter choice*

$$r := c_{F.1} r_G, \quad \delta = c_{F.1} r, \quad \eta = c_{F.1} \delta,$$

and

$$m := \mu_{\min}(c_{C.5} \eta^2 / 3) \frac{n}{2}.$$

Let $V_{\text{ocn}} \subseteq \mathbf{V}$ with $|V_{\text{ocn}}| = 2n + n_{\text{cn}}$, where n_{cn} is introduced in Algorithm 2. Let Ω_{ocn} be the event running partitioning V_{ocn} into 3 parts V_{cn} , V_{net} and V_{ortho} and then running Algorithm 2 on $V_{\text{cn}} \sqcup V_{\text{net}} \sqcup V_{\text{ortho}}$ with parameters r, δ, η, m outputs

- A family $\{(U_i, u_i)\}_{i=1}^k \subseteq V_{\text{ocn}}$ with $|U_i| \geq m$ and $\mathcal{E}_{\text{clu}}(\eta, U_i, u_i)$. Their centers form a 2δ -net of M : $\{X_{u_i}\}_{i=1}^k$ is 2δ net of M with δ -separation.
- Let $\{(V_j, v_j)\}_{j=1}^\ell \subseteq V_{\text{ocn}}$ with $|V_j| \geq m$ and $\mathcal{E}_{\text{clu}}(\eta, V_j, v_j)$. For each $i \in [k]$ there is a map $\text{ax}_i : [d] \rightarrow [\ell]$ such that the orthogonal-frame event $\mathcal{E}_\perp(r, \delta, \eta, (u_i, v_{\text{ax}_i(1)}, \dots, v_{\text{ax}_i(d)}))$ holds, namely:

$$\begin{cases} ||X_{u_i} X_{v_{\text{ax}_i(\alpha)}}| - r| \leq \delta & \forall \alpha \in [d] \\ ||X_{v_{\text{ax}_i(\alpha)}} X_{v_{\text{ax}_i(\beta)}}| - \sqrt{2}r| \leq \delta & \forall \alpha, \beta \in [d], \alpha \neq \beta \end{cases}$$

Let $V_{\text{fine}} \subseteq \mathbf{V}$ with $|V_{\text{fine}}| = n$ be disjoint from V_{ocn} . Assume Ω_{ocn} , $\mathcal{E}_{\text{navi}}(U_i, V_{\text{fine}})$ and $\mathcal{E}_{\text{navi}}(V_j, V_{\text{fine}})$ for all $i \in [k]$, $j \in [\ell]$, and $\mathcal{E}_{\text{pt}}(V_{\text{fine}})$. We set

$$\xi := c_{G.1} \left(\frac{\log n}{s_n n} \right)^{1/(d+2)}. \quad (55)$$

The Algorithm 3, which takes the edges

$$E(U_i, V_{\text{fine}}), \quad E(V_j, V_{\text{fine}}) \quad (i \in [k], j \in [\ell]),$$

as input, returns clusters $\{(W_w, w)\}_{w \in V_{\text{fine}}}$ with $W_w \subseteq V_{\text{fine}}$ such that each W_w satisfies $\mathcal{E}_{\text{clu}}(\xi, W_w, w)$ and its size satisfies the size calibration margin (11):

$$\varepsilon_{W_w} \leq \ell_p \xi.$$

Remark G.2 If we denote by Ω_{fine} the event that the composition of Algorithm 2 and Algorithm 3 satisfies the properties in Proposition G.1, then we have

$$\mathbb{P}(\Omega_{\text{fine}}) = 1 - n^{-\omega(1)}.$$

This is simply due to conditional independence. First, Ω_{ocn} holds with probability $1 - n^{-\omega(1)}$ by Proposition F.1, and is an event of $X_{V_{\text{ocn}}}$ and $\mathcal{U}_{V_{\text{ocn}}, V_{\text{ocn}}}$. Second, $\mathcal{E}_{\text{pt}}(V_{\text{fine}})$, as an event of $X_{V_{\text{fine}}}$, is independent of Ω_{ocn} and holds with probability $1 - n^{-\omega(1)}$ by Lemma A.9, which implies

$$\Pr(\Omega_{\text{ocn}} \cap \mathcal{E}_{\text{pt}}(V_{\text{fine}})) = 1 - n^{-\omega(1)}.$$

Third, the events $\mathcal{E}_{\text{navi}}(U_i, V_{\text{fine}})$ and $\mathcal{E}_{\text{navi}}(V_j, V_{\text{fine}})$ for all $i \in [k]$ and $j \in [\ell]$ are all events of $\mathcal{U}_{U_i, V_{\text{fine}}}$ and $\mathcal{U}_{V_j, V_{\text{fine}}}$, which are independent, conditioning of $X_{V_{\text{ocn}} \cup V_{\text{fine}}}$ and $\mathcal{U}_{V_{\text{ocn}}, V_{\text{ocn}}}$. Therefore, by Lemma A.2 and union bound, we have

$$\Pr\left(\bigcap_{i=1}^k \mathcal{E}_{\text{navi}}(U_i, V_{\text{fine}}) \cap \bigcap_{j=1}^{\ell} \mathcal{E}_{\text{navi}}(V_j, V_{\text{fine}}) \mid \Omega_{\text{ocn}} \cap \mathcal{E}_{\text{pt}}(V_{\text{fine}})\right) = 1 - n^{-\omega(1)},$$

which implies Ω_{fine} holds with probability $1 - n^{-\omega(1)}$.

The algorithm is straightforward. For each $w \in V_{\text{fine}}$ and choose $i(w) \in [k]$ such that

$$N_{U_{i(w)}}(w) \geq p(3\delta),$$

and set

$$u^w := u_{i(w)}, \quad U^w := U_{i(w)}, \quad v_{\alpha}^w := v_{\mathbf{a} \times i(w)(\alpha)}, \quad V_{\alpha}^w := V_{\mathbf{a} \times i(w)(\alpha)} \quad (\alpha \in [d]).$$

Define, for $v \in V_{\text{fine}}$,

$$\psi_w(v) := \sqrt{\sum_{\alpha=1}^d (N_{V_{\alpha}^w}(v) - N_{V_{\alpha}^w}(w))^2},$$

and for a threshold λ (to be specified below),

$$W_w := \left\{ v \in V_{\text{fine}} : N_{U^w}(v) \geq p(9\delta) \text{ and } \psi_w(v) \leq \lambda \right\}.$$

We assume throughout that

$$4\sqrt{d}\varepsilon_m \leq \lambda \leq \eta^2,$$

which is feasible for all large n under our parameter configuration (since η is a fixed small constant and $\varepsilon_m = o(1)$). The precise choice of λ is given in the algorithm and derived in the proof below.

Algorithm 3: refine-fine: axis-guided local clustering on V_{fine}
Input : $\{(U_i, u_i)\}_{i \in [k]}$, $\{(V_j, v_j)\}_{j \in [\ell]}$, and axis maps $\{\text{ax}_i : [d] \rightarrow [\ell]\}_{i \in [k]}$
 Fresh set $V_{\text{fine}} \subseteq \mathbf{V}$ with $|V_{\text{fine}}| = n$, disjoint from all clusters.
 Edges $E(U_i, V_{\text{fine}})$ and $E(V_j, V_{\text{fine}})$ for all $i \in [k]$, $j \in [\ell]$.
 Parameters r, δ, η (standing choice tied to $c_{\text{F.1}}$), integer m .
Output: Refined local clusters $\{(W_w, w)\}_{w \in V_{\text{fine}}}$ with $W_w \subseteq V_{\text{fine}}$.

Initialization:

```

 $\lambda \leftarrow \left( \frac{\sqrt{2}(18L_p)^{d/2}}{6\sqrt{c_\mu}} \cdot \frac{\log n}{\sqrt{s_n n}} \right)^{\frac{2}{d+2}}$   foreach  $w \in V_{\text{fine}}$  do
    // Choose reference net cluster via a coarse proximity test
     $i(w) \leftarrow \arg \max_{i \in [k]} \mathbf{1}\{N_{U_i}(w) \geq p(3\delta)\};$ 
    if no such  $i$  exists then
        | return failure (no cluster found around  $w$ );
    end
     $U^w \leftarrow U_{i(w)}; u^w \leftarrow u_{i(w)}$  for  $\alpha \in [d]$  do
        |  $V_\alpha^w \leftarrow V_{\text{ax}_i(w)(\alpha)}; v_\alpha^w \leftarrow v_{\text{ax}_i(w)(\alpha)}$ 
    end
    // Define the axis-based difference functional  $\psi_w$ 
    foreach  $v \in V_{\text{fine}}$  do
        |  $\psi_w(v) \leftarrow \sqrt{\sum_{\alpha=1}^d (N_{V_\alpha^w}(v) - N_{V_\alpha^w}(u^w))^2}$ 
    end
    // Select the refined cluster around  $w$ 
     $W_w \leftarrow \{v \in V_{\text{fine}} : N_{U^w}(v) \geq p(9\delta) \wedge \psi_w(v) \leq \lambda\}$ 
end
return  $\{(W_w, w)\}_{w \in V_{\text{fine}}}$ .
    
```

Remark G.3 The running time of Algorithm 3 is $O(n^2)$ where the dominant step is to compute the edges $N_{U^w}(v)$ and $N_{V_\alpha^w}(v)$ for all $w, v \in V_{\text{fine}}$ and $\alpha \in [d]$.

Proof Step 1: From $N_{U^w}(w) \geq p(3\delta)$ to a bound on $|X_w X_{u^w}|$. First, we know there exists

$i \in [k]$ such that $|X_w X_{u_i}| \leq 2\delta$ by the event that $\{X_{u_i}\}_{i=1}^k$ is a 2δ -net of M . Fix such i , with $\mathcal{E}_{\text{clu}}(\eta, U_i, u_i)$ and $\mathcal{E}_{\text{navi}}(U_i, V_{\text{fine}})$, the Calibration Lemma A.6 gives

$$N_{U_i}(w) \geq p(2\delta + \eta) - \varepsilon_{U_i} \geq p(3\delta),$$

which guarantees $i(w)$ is well-defined. Now, with the choice of $i(w)$, the Calibration Lemma A.6 gives

$$|X_w X_{u^w}| \leq 3\delta + 2\eta \leq 4\delta,$$

for $c_{\text{F.1}}$ small enough.

Step 2: A convenient geometric inclusion. For any $v \in V_{\text{fine}}$ with $|X_v X_w| \leq \delta$, the triangle inequality and Step 1 give

$$|X_v X_{u^w}| \leq |X_v X_w| + |X_w X_{u^w}| \leq \delta + 4\delta = 5\delta.$$

By monotonicity of p , the bracket $p(|X_v X_{u^w}| + \eta) \leq p_{U^w}(v) \leq p(|X_v X_{u^w}| - \eta)$ (see (14)) and $\varepsilon_{U^w} \leq \ell_p \eta$, we obtain

$$N_{U^w}(v) \geq p_{U^w}(v) - \varepsilon_{U^w} \geq p(5\delta + \eta) - \varepsilon_{U^w} \geq p(9\delta), .$$

Therefore,

$$B_{5\delta}(w) \cap V_{\text{fine}} \subseteq \{v \in V_{\text{fine}} : N_{U^w}(v) \geq p(9\delta)\}. \quad (56)$$

Step 3: Navigation via the orthogonal frame (Scenario 2). On Ω_{ocn} , the family $\{(U^w, u^w), (V_\alpha^w, v_\alpha^w)\}_{\alpha \in [d]}$ is an approximate orthogonal frame. Thus Proposition E.1 applies (using $\mathcal{E}_{\text{navi}}(U^w, \{w, v\})$ and $\mathcal{E}_{\text{navi}}(V_\alpha^w, \{w, v\})$), yielding for all $v \in V_{\text{fine}}$ with $N_{U^w}(v) \geq p(9\delta)$,

$$\frac{\ell_p}{3} |X_w X_v| - 2\sqrt{d} \varepsilon_m \leq \psi_w(v) \leq 3L_p |X_w X_v| + 2\sqrt{d} \varepsilon_m. \quad (57)$$

Step 4: Inner and outer radii for W_w . Assume $\lambda \geq 4\sqrt{d} \varepsilon_m$. Then from the upper bound in (57),

$$|X_w X_v| \leq \frac{\lambda}{6L_p} \implies \psi_w(v) \leq \frac{\lambda}{2} + 2\sqrt{d} \varepsilon_m \leq \lambda,$$

so every $v \in V_{\text{fine}}$ with $|X_v X_w| \leq \lambda/(6L_p)$ and $N_{U^w}(v) \geq p(9\delta)$ lies in W_w . Since $\lambda \leq \eta \ll \delta$, this ball is contained in $B_{5\delta}(w)$, hence by (56),

$$B_{\lambda/(6L_p)}(w) \cap V_{\text{fine}} \subseteq W_w. \quad (58)$$

Conversely, if $|X_v X_w| \geq \frac{6\lambda}{\ell_p}$, then the lower bound in (57) and $\lambda \geq 4\sqrt{d} \varepsilon_m$ imply

$$\psi_w(v) \geq 2\lambda - 2\sqrt{d} \varepsilon_m \geq \frac{3}{2}\lambda > \lambda,$$

so such v cannot belong to W_w . Therefore,

$$W_w \subseteq B_{6\lambda/\ell_p}(w) \cap V_{\text{fine}}. \quad (59)$$

In particular, $\mathcal{E}_{\text{clu}}(6\lambda/\ell_p, W_w, w)$ holds.

Step 5: Size lower bound for W_w . By (58) and the point-count event $\mathcal{E}_{\text{pt}}(V_{\text{fine}})$,

$$|W_w| \geq |B_{\lambda/(6L_p)}(w) \cap V_{\text{fine}}| \geq \mu_{\min}\left(\frac{\lambda}{18L_p}\right) \frac{n}{2}. \quad (60)$$

With $\lambda/(18L_p) \leq \frac{\eta}{18L_p} \ll r_\mu$, the standing assumption $\mu_{\min}(r) \geq c_\mu r^d$ yields

$$|W_w| \geq \frac{c_\mu}{2} \left(\frac{\lambda}{18L_p}\right)^d n.$$

Step 6: Fluctuation level inside W_w and the balanced choice of λ . Using the definition $\varepsilon_U =$

$\frac{\log n}{\sqrt{s_n}|U|}$ and (60), we get

$$\varepsilon_{W_w} \leq \frac{\sqrt{2} \log n}{\sqrt{c_\mu s_n n}} \left(\frac{18L_p}{\lambda}\right)^{d/2}.$$

Recall that if we treat (W^w, w) as a cluster and within the event $\mathcal{E}_{\text{navi}}(W^w, v)$ for some vertex v , then

$$|\mathbf{N}_{W^w}(v) - \mathbf{p}_{W^w}(v)| \leq \frac{\varepsilon_{W^w}}{\ell_p} + \frac{6\lambda}{\ell_p}.$$

So a convenient “balanced” choice of λ is obtained by imposing $\varepsilon_{W^w} = 6\lambda$. Define

$$\lambda_{\text{bal}} := \left(\frac{\sqrt{2}(18L_p)^{d/2}}{6\sqrt{c_\mu}} \cdot \frac{\log n}{\sqrt{s_n n}} \right)^{\frac{2}{d+2}}. \quad (61)$$

Finally set

$$\lambda := \min \left\{ \eta, \max \{ 4\sqrt{d} \varepsilon_m, \lambda_{\text{bal}} \} \right\} = \max \{ 4\sqrt{d} \varepsilon_m, \lambda_{\text{bal}} \} = \lambda_{\text{bal}}, \quad (62)$$

where the last inequality holds for all sufficiently large n since

$$\lambda_{\text{bal}} = \Theta \left(\left(\frac{\log n}{\sqrt{s_n n}} \right)^{2/(d+2)} \right) \text{ while } \varepsilon_m = \Theta \left(\frac{\log n}{\sqrt{s_n n}} \right).$$

For all sufficiently large n , λ satisfies $4\sqrt{d} \varepsilon_m \leq \lambda \leq \eta$, hence Steps 4–6 apply and give

$$\mathcal{E}_{\text{clu}} \left(\frac{6\lambda}{\ell_p}, W_w, w \right), \quad |W_w| \geq \mu_{\min} \left(\frac{\lambda}{18L_p} \right) \frac{n}{2}, \quad \varepsilon_{W_w} \leq 6\lambda.$$

Replacing λ by $\frac{6\lambda}{\ell_p}$ concludes the proof of Proposition G.1. ■

We conclude this section by stating a byproduct which will be used later estimate the pairwise distances between any two points.

Algorithm 4: refine-fine-net: greedy extraction of a ζ -net on V_{fine}

Input : $\{(U_i, u_i)\}_{i \in [k]}$, $\{(V_j, v_j)\}_{j \in [\ell]}$, and axis maps $\{\mathbf{a}_i : [d] \rightarrow [\ell]\}_{i \in [k]}$;
 Fresh set $V_{\text{fine}} \subseteq \mathbf{V}$ with $|V_{\text{fine}}| = n$, disjoint from V_{ocn} ;
 Edges $E(U_i, V_{\text{fine}})$ and $E(V_j, V_{\text{fine}})$ for all $i \in [k], j \in [\ell]$;
 Parameters r, δ, η, m (standing choice tied to $c_{\text{F.1}}$);
 A scale ζ with $C_{\text{G.4}} \varepsilon_m \leq \zeta \leq \eta$.

Output: A subset $S \subseteq V_{\text{fine}}$ such that $\{X_w : w \in S\}$ is a ζ -net of M with $\frac{1}{18L_p} \zeta$ -separation (on Ω_{ocn}).

Precomputation (axis setup and local gauges):

```

foreach  $w \in V_{\text{fine}}$  do
    // Choose a reference net cluster for  $w$ 
     $i(w) \leftarrow \arg \max_{i \in [k]} \mathbf{1}\{N_{U_i}(w) \geq p(3\delta)\}$ ;
     $U^w \leftarrow U_{i(w)}$ ;  $u^w \leftarrow u_{i(w)}$ ;
    for  $\alpha \in [d]$  do
         $V_\alpha^w \leftarrow V_{\mathbf{a}_{i(w)}(\alpha)}$ ;  $v_\alpha^w \leftarrow v_{\mathbf{a}_{i(w)}(\alpha)}$ ;
    end
    // Define the axis-based difference functional  $\psi_w$ 
    foreach  $v \in V_{\text{fine}}$  do
         $\psi_w(v) \leftarrow \sqrt{\sum_{\alpha=1}^d (N_{V_\alpha^w}(v) - N_{V_\alpha^w}(w))^2}$ ;
    end
end

```

Greedy selection:

```

 $\tau \leftarrow 10L_p \zeta$ ; // separation threshold from Lemma G.4
 $S \leftarrow \emptyset$ ;  $A \leftarrow V_{\text{fine}}$ ; //  $A$  = uncovered points
 $t \leftarrow 0$  while  $A \neq \emptyset$  do
     $t \leftarrow t + 1$ ; pick any  $w_t \in A$ ; // arbitrary choice
     $S \leftarrow S \cup \{w_t\}$ ;
    // Mark points covered by  $w_t$  (close in the coarse test & small axis discrepancy)
     $\text{Cover}(w_t) \leftarrow \{v \in A : N_{U^{w_t}}(v) \geq p(9\delta) \wedge \psi_{w_t}(v) < \tau\}$ ;
     $A \leftarrow A \setminus \text{Cover}(w_t)$ ;
end
return  $(S, (\text{Cover}(w))_{w \in S})$ .

```

Lemma G.4 Under the same notation and assumptions as in Proposition G.1, there exists a constant $C_{\text{G.4}} > 0$, depending on L_p, ℓ_p , and d , such that the following holds. For any

$$C_{\text{G.4}} \varepsilon_m \leq \zeta \leq \eta,$$

on the event Ω_{ocn} and $\mathcal{E}_{\text{pt}}(V_{\text{fine}})$, the Algorithm 4 returns a collection $(\text{Cover}(w), w)_{w \in S}$ for some subset $S \subseteq V_{\text{fine}}$ such that S is a 2ζ -separation. Further, for each $w \in S$ and $v \in \text{Cover}(w)$,

$$|X_w X_v| \leq C_{\text{G.4}} \zeta.$$

Proof of Lemma G.4 As established in the proof of Proposition G.1, for any $w, v \in V_{\text{fine}}$ with $|X_w X_v| \leq \delta$, we have

$$N_{U^w}(w') \geq p(9\delta), \quad \text{and} \quad \frac{\ell_p}{3} |X_w X_v| - 2\sqrt{d} \varepsilon_m \leq \psi_w(v) \leq 3L_p |X_w X_v| + 2\sqrt{d} \varepsilon_m.$$

We now construct S via a greedy selection procedure. Start with an arbitrary singleton $\{w_1\} \subseteq V_{\text{fine}}$, and iteratively add $w_{i+1} \in V_{\text{fine}}$ such that for all $s \in [i]$,

$$\psi_{w_s}(w_{i+1}) \geq 10L_p\zeta \quad \text{or} \quad N_{U^{w_s}}(w_{i+1}) < p(9\delta).$$

This construction ensures that for any two distinct points $w, w' \in S$,

$$|X_w X_{w'}| \geq 2\zeta$$

where the last inequality follows from the assumption $\zeta \geq C\varepsilon_m$. (In the case when $N_{U^{w_s}}(w_{i+1}) < p(9\delta)$, we simply have $|X_{w_s} X_{w_{i+1}}| \geq 8\delta > \zeta$.)

On the other hand, for each $w' \in \text{Cover}(w)$, we have

$$|X_{w'} X_w| \leq C\zeta,$$

when C is a sufficiently large constant depending on L_p and ℓ_p .

Next, suppose that there exists a vertex $w \in V_{\text{fine}} \setminus S$ such that $|X_{w'} X_w| \geq \zeta/2$ for all $w' \in S$. Then for each $w' \in S$, we must have either $\psi_{w'}(w) \leq \frac{\ell_p}{3}\frac{\zeta}{2} - 2\sqrt{d}\varepsilon_m$ or $N_{U^{w'}}(w) \leq p(9\delta)$, contradicting the maximality of S . Therefore, S is a $\zeta/2$ -net of $\{X_v\}_{v \in V_{\text{fine}}}$.

Finally, by the event $\mathcal{E}_{\text{pt}}(V_{\text{fine}})$, every point $q \in M$ lies within distance

$$\left(\frac{\log^2 n}{n}\right)^{1/d} \ll \frac{\zeta}{2}$$

of some X_v , implying that S is indeed a ζ -net of M . ■

Appendix H. From clusters to distance estimates

Setup and objective. From now on assume $|\mathbf{V}| = 4n$. Suppose we fix a partition $\mathbf{V} = V_{\text{ocn}} \dot{\cup} V_{\text{fine}}$ with $|V_{\text{ocn}}| = 3n$ and $|V_{\text{fine}}| = n$. Applying the previous two stages (Algorithm 2 on V_{ocn} and the refinement procedure on V_{fine}) yields a family of clusters

$$\{(W_w, w)\}_{w \in V_{\text{fine}}}, \quad W_w \subseteq V_{\text{fine}},$$

such that each W_w satisfies

$$\mathcal{E}_{\text{clu}}(\xi, W_w, w) \quad \text{and} \quad \varepsilon_{W_w} \leq \ell_p \xi,$$

These clusters allow us to estimate pairwise distances within V_{fine} with high accuracy whenever the latent distance lies in the bi-Lipschitz window of p (via the Calibration Lemma). The goal of this section is to push beyond these two limitations:

1. to extend the estimator *beyond* the bi-Lipschitz regime of p , by stitching together local distance estimates along paths, and
2. to produce a *fine distance estimator* for *every* pair $v, w \in \mathbf{V}$ (rather than just those in V_{fine}).

The resolution of the both issues are rather straightforward. Suppose we have a distance estimator $d(w, v)$ for all $w, v \in V_{\text{fine}}$ whose latent distances are within r_G . Then, we build a weighted graph on V_{fine} with edge weights $d(w, v)$ for all $w, v \in V_{\text{fine}}$ with $|X_w X_v| \lesssim r_G$, and ∞ otherwise. The shortest-path distance on this graph will be a good distance estimator for all pairs $w, v \in V_{\text{fine}}$, with no restriction on the latent distance.

For the second issues, we will simply partition $\mathbf{V}$ into 8 equal parts with each part of size n . Then we run the above two-stage algorithms on every combination of V_{fine} being the union of two parts and V_{ocn} being the union of the other six parts. This way, every pair $v, w \in \mathbf{V}$ will be contained in some version of V_{fine} . Overall, we will run the two-stage algorithms $\binom{8}{2}$ times. The overall procedure is summarized in Algorithm 5.

Algorithm 5: fine distance

Input : $\mathbf{V}$ with $|\mathbf{V}| = 4n$.

Edges $E(\mathbf{V}, \mathbf{V})$.

Parameters r, δ, η , integer m .

Output: s

```

 $\xi \leftarrow c_{\text{G.1}} \left( \frac{\log n}{s_n n} \right)^{1/(d+2)}$  Initialize  $w^{\alpha, \beta} : \mathbf{V} \rightarrow \mathbb{R}_{\geq 0}$  by  $w^{\alpha, \beta}(w, v) \leftarrow \infty$  for all  $w, v \in \mathbf{V}$  and
 $\{\alpha, \beta\} \in \binom{[8]}{2}$  Partition  $\mathbf{V}$  into 8 equal parts with each part of size  $n$ :  $\mathbf{V}_1, \dots, \mathbf{V}_8$  foreach
 $\{\alpha, \beta\} \subseteq \binom{[8]}{2}$  do
     $V_{\text{fine}} \leftarrow \mathbf{V}_\alpha \cup \mathbf{V}_\beta$   $V_{\text{ocn}} \leftarrow \mathbf{V} \setminus V_{\text{fine}}$  Randomly select disjoint subsets  $V_{\text{cn}}, V_{\text{net}}, V_{\text{ortho}}$  from  $V_{\text{ocn}}$ 
    with  $|V_{\text{cn}}| = n_{\text{cn}}$  (see (49)),  $|V_{\text{net}}| = |V_{\text{ortho}}| = n$  ( $\{(U_i, u_i)\}_{i \in [k]}, \{(V_j, v_j)\}_{j \in [\ell]}, \{\mathbf{a}\mathbf{x}_i : [d] \rightarrow [\ell]\}_{i \in [k]} \leftarrow \text{cluster-net}(V_{\text{cn}}, V_{\text{net}}, V_{\text{ortho}}, r, \delta, \eta, m, E(V_{\text{ocn}}))$ 
     $\{(W_w^{\alpha, \beta}, w)\}_{w \in V_{\text{fine}}} \leftarrow \text{refine-fine}(\{(U_i, u_i)\}_{i \in [k]}, \{(V_j, v_j)\}_{j \in [\ell]}, \{\mathbf{a}\mathbf{x}_i\}_{i \in [k]}, V_{\text{fine}}, E(U_i, V_{\text{fine}}), E(V_j, V_{\text{fine}}), r, \delta, \eta, m)$ 
     $(S, (\text{Cover}(w))_{w \in S}) \leftarrow \text{refine-fine-net}(\{(U_i, u_i)\}_{i \in [k]}, \{(V_j, v_j)\}_{j \in [\ell]}, \{\mathbf{a}\mathbf{x}_i\}_{i \in [k]}, V_{\text{fine}}, E(U_i, V_{\text{fine}}), E(V_j, V_{\text{fine}}), r, \delta, \eta, \xi)$ 
    foreach  $w \in V_{\text{fine}}$  do
         $w' \leftarrow$  the unique element in  $S$  such that  $w \in \text{Cover}(w')$  foreach  $v \in V_{\text{fine}}$  do
             $v' \leftarrow$  the unique element in  $S$  such that  $v \in \text{Cover}(v')$  if  $v' = w'$  then
                 $w^{\alpha, \beta}(w, v) \leftarrow C_{\text{G.4}} \xi$ 
            end
            else if  $N_{W_w^{\alpha, \beta}}(v) \geq p(r_G)$  then
                 $w^{\alpha, \beta}(w, v) \leftarrow p^{-1}(N_{W_w^{\alpha, \beta}}(v)) + 2\xi + 2C_{\text{G.4}} \xi$ 
            end
        end
    end
end
 $w(w, v) \leftarrow \min\{w^{\alpha, \beta}(w, v), w^{\alpha, \beta}(v, w)\}_{\{\alpha, \beta\} \in \binom{[8]}{2}} \quad \forall w, v \in \mathbf{V}$ 
 $(d(w, v))_{w, v \in \mathbf{V}} \leftarrow \text{Dijkstra}((w(w, v))_{w, v \in \mathbf{V}})$  return  $(d(w, v))_{w, v \in \mathbf{V}}$ 
    
```

Remark H.1 We remark that, excluding the final all-pairs shortest-path computation, the running time of Algorithm 5 is $O(n^2 \log^2 n)$, where the dominant step is to run Algorithm 3 for $\binom{8}{2}$ times. Including the final shortest-path step, the running time is $O(n^3)$.

Here we restate Theorem 1.6 and provide its proof.

Theorem Assuming that $s_n n = \omega(\log^2 n)$. The following holds when n is sufficiently large. Running Algorithm 5 on $\mathbf{V}$ with $|\mathbf{V}| = 4n$ and edges $E(\mathbf{V}, \mathbf{V})$ returns a distance estimator

$(d(w, v))_{w, v \in \mathbf{V}}$ such that, with probability $1 - n^{-\omega(1)}$, for all $w, v \in \mathbf{V}$,

$$||X_w X_v| - d(w, v)| \leq C \left(\frac{\log^2 n}{s_n n} \right)^{\frac{1}{d+2}}$$

where C is a constant depending only on $d, L_p, \ell_p, c_\mu, r_G$, and $\text{diam}(M)$.

Proof of Theorem 1.6 Good event for each run of the two-stage algorithms. Fix $\{\alpha, \beta\} \in \binom{[8]}{2}$. Let

$$\Omega_{\text{fine}}^{\alpha, \beta}$$

be the event of $X_{\mathbf{V}}$ and $\mathcal{U}_{\mathbf{V} \setminus \mathbf{V}_\alpha \cup \mathbf{V}_\beta, \mathbf{V}}$ (excluding $\mathcal{U}_{\mathbf{V}_\alpha \cup \mathbf{V}_\beta, \mathbf{V}_\alpha \cup \mathbf{V}_\beta}$) that

$$\mathcal{E}_{\text{pt}}(\mathbf{V}_\alpha \cup \mathbf{V}_\beta), \quad \mathcal{E}_{\text{clu}}(\xi, W_w^{\alpha, \beta}, w), \quad \varepsilon_{W_w^{\alpha, \beta}} \leq \ell_p \xi \quad \text{for all } w \in \mathbf{V}_\alpha \cup \mathbf{V}_\beta,$$

where

$$\xi = c_{\mathbf{G}.1} \left(\frac{\log n}{s_n n} \right)^{1/(d+2)}$$

was defined in Proposition G.1. This event holds with probability $1 - n^{-\omega(1)}$ by Proposition G.1 and Remark G.2. Now, fix any realization of $X_{\mathbf{V}} = x_{\mathbf{V}}$ and $\mathcal{U}_{\mathbf{V} \setminus \mathbf{V}_\alpha \cup \mathbf{V}_\beta, \mathbf{V}} = \mathbf{u}_{\mathbf{V} \setminus \mathbf{V}_\alpha \cup \mathbf{V}_\beta, \mathbf{V}}$ such that $\Omega_{\text{fine}}^{\alpha, \beta}$. Given that $\mathcal{U}_{\mathbf{V}_\alpha \cup \mathbf{V}_\beta, \mathbf{V}_\alpha \cup \mathbf{V}_\beta}$ is independent of $X_{\mathbf{V}}$ and $\mathcal{U}_{\mathbf{V} \setminus \mathbf{V}_\alpha \cup \mathbf{V}_\beta, \mathbf{V}}$, by Lemma A.2 and union bound, we have

$$\Pr \left(\bigcap_{w \in \mathbf{V}_\alpha \cup \mathbf{V}_\beta} \mathcal{E}_{\text{navi}}(W_w^{\alpha, \beta}, \mathbf{V}_\alpha \cup \mathbf{V}_\beta \setminus W_w^{\alpha, \beta}) \mid X_{\mathbf{V}} = x_{\mathbf{V}}, \mathcal{U}_{\mathbf{V} \setminus \mathbf{V}_\alpha \cup \mathbf{V}_\beta, \mathbf{V}} = \mathbf{u}_{\mathbf{V} \setminus \mathbf{V}_\alpha \cup \mathbf{V}_\beta, \mathbf{V}} \right) = 1 - n^{-\omega(1)}.$$

Given this conditional probability holds for all realizations of $X_{\mathbf{V}}$ and $\mathcal{U}_{\mathbf{V} \setminus \mathbf{V}_\alpha \cup \mathbf{V}_\beta, \mathbf{V}}$ such that $\Omega_{\text{fine}}^{\alpha, \beta}$, we have

$$\Omega_{\text{dist}}^{\alpha, \beta} := \Omega_{\text{fine}}^{\alpha, \beta} \cap \bigcap_{w \in \mathbf{V}_\alpha \cup \mathbf{V}_\beta} \mathcal{E}_{\text{navi}}(W_w^{\alpha, \beta}, \mathbf{V}_\alpha \cup \mathbf{V}_\beta \setminus W_w^{\alpha, \beta})$$

holds with probability $1 - n^{-\omega(1)}$.

Distance estimates with $\mathbf{w}^{\alpha, \beta}$. Fix any realization of the graph such that $\Omega_{\text{dist}}^{\alpha, \beta}$ holds. From $\mathcal{E}_{\text{clu}}(\xi, W_w^{\alpha, \beta}, w)$, $\varepsilon_{W_w^{\alpha, \beta}} \leq \ell_p \xi$, and $\mathcal{E}_{\text{navi}}(W_w^{\alpha, \beta}, \mathbf{V}_\alpha \cup \mathbf{V}_\beta \setminus W_w^{\alpha, \beta})$, the Calibration Lemma A.6 gives, for all $w, v \in \mathbf{V}_\alpha \cup \mathbf{V}_\beta$ with $v \notin W_w^{\alpha, \beta}$ and $N_{W_w^{\alpha, \beta}}(v) \geq p(r_G)$,

$$|p^{-1}(N_{W_w^{\alpha, \beta}}(v)) - |X_w X_v|| \leq 2\xi.$$

In the case $v \in W_w^{\alpha, \beta}$, we have $|X_w X_v| \leq \xi$ by $\mathcal{E}_{\text{clu}}(\xi, W_w^{\alpha, \beta}, w)$. Therefore, from our definition

$$\mathbf{w}^{\alpha, \beta}(w, v) = \begin{cases} \xi, & v \in W_w^{\alpha, \beta}, \\ p^{-1}(N_{W_w^{\alpha, \beta}}(v)) + 2\xi, & v \notin W_w^{\alpha, \beta}, N_{W_w^{\alpha, \beta}}(v) \geq p(r_G), \\ +\infty, & \text{otherwise,} \end{cases}$$

we have the implication

$$w^{\alpha,\beta}(w, v) < +\infty \implies w^{\alpha,\beta}(w, v) \geq |X_w X_v| \geq w^{\alpha,\beta}(w, v) - 4\xi. \quad (63)$$

Small distance guarantees for $w^{\alpha,\beta}$. Further, whenever $|X_w X_v| \leq r_G/2$, if $v \notin W_w^{\alpha,\beta}$, then our Calibration Lemma A.6 gives

$$N_{W_w^{\alpha,\beta}}(v) \geq p(|X_w X_v| + 2\eta) \geq p(r_G) \quad (\text{since } \eta \ll r_G).$$

Therefore,

$$|X_w X_v| \leq r_G/2 \implies w^{\alpha,\beta}(w, v) < +\infty. \quad (64)$$

Conclusion for $w(w, v)$. Now, we assume the good event

$$\Omega_{\text{dist}} := \bigcap_{\{\alpha,\beta\} \in \binom{[8]}{2}} \Omega_{\text{dist}}^{\alpha,\beta}$$

holds, which happens with probability $1 - n^{-\omega(1)}$ by union bound. Then, from (63), the definition

$$w(w, v) := \min\{w^{\alpha,\beta}(w, v), w^{\alpha,\beta}(v, w)\}_{\{\alpha,\beta\} \in \binom{[8]}{2}} \quad \forall w, v \in \mathbf{V},$$

implies that

$$w(w, v) < +\infty \implies w(w, v) \geq |X_w X_v| \geq w(w, v) - 4\xi. \quad (65)$$

Furthermore, whenever $w, v \in \mathbf{V}$ satisfy $|X_w X_v| \leq r_G/2$, there exists $\{\alpha, \beta\} \in \binom{[8]}{2}$ such that $w, v \in \mathbf{V}_\alpha \cup \mathbf{V}_\beta$. Then, from (64), we have

$$|X_w X_v| \leq r_G/2 \implies w(w, v) < +\infty. \quad (66)$$

Final distance estimator $d(w, v)$. Finally, we define the distance estimator $d(w, v)$ for all $w, v \in \mathbf{V}$ as the shortest-path distance with respect to the edge weights $w(w, v)$. Fix any $w, v \in \mathbf{V}$. Let γ be a shortest geodesic from X_w to X_v in M and let $t = \left\lceil \frac{|X_w X_v|}{r_G} \right\rceil$. Let $p_0 = X_w, p_1, \dots, p_t = X_v$ be equidistant points on γ such that $|p_{i-1} p_i| = |X_w X_v|/t \leq r_G/2$ for all $i = 1, \dots, t$. By the event $\mathcal{E}_{\text{pt}}(\mathbf{V})$, there exist $w = u_0, u_1, \dots, u_t = v$ in $\mathbf{V}$ such that

$$|X_{u_i} p_i| \leq \left(\frac{\log^2(n)}{n} \right)^{1/d} = o(\xi)$$

for all $i = 1, \dots, t-1$. Then, by triangle inequality,

$$\begin{aligned} |X_w X_v| &= \sum_{i=1}^t |p_{i-1} p_i| \geq \sum_{i=1}^t \left(|X_{u_{i-1}} X_{u_i}| - 2 \left(\frac{\log^2(n)}{n} \right)^{1/d} \right) \\ &\geq \sum_{i=1}^t \left(w(u_{i-1}, u_i) - 5\xi \right) \geq d(w, v) - \frac{\text{diam}(M)}{r_G/2} \cdot 5\xi. \end{aligned}$$

On the other hand, let $w = z_0, z_1, \dots, z_s = v$ in $\mathbf{V}$ be the path that attains the shortest-path distance $d(w, v)$. Then by (66), we have

$$|X_w X_v| \leq \sum_{i=1}^s |X_{z_{i-1}} X_{z_i}| \leq \sum_{i=1}^s w(z_{i-1}, z_i) = d(w, v).$$

Together we conclude that under the event Ω_{dist} , for all $w, v \in \mathbf{V}$,

$$|X_w X_v| \leq d(w, v) \leq |X_w X_v| + 10 \frac{\text{diam}(M)}{r_G} \xi.$$

■

Appendix I. Auxiliary Geometric Results

This section provides some auxiliary results from Riemannian geometry. We start with a standard proposition about the exponential map.

Proposition I.1 ((Cheeger and Ebin, 2008, Corollary 1.9)) *Let $B_r(\mathbf{0}) \subseteq T_p M$ be the open ball of radius r on which the exponential map $\exp_p$ is an embedding. Then*

1. *For every $v \in B_r(\mathbf{0})$, the curve*

$$\gamma_v : [0, 1] \longrightarrow M, \quad \gamma_v(t) = \exp_p(tv),$$

is the unique curve satisfying

$$L[\gamma_v] = \rho(p, \exp_p(v)) = \|v\|$$

such that $\gamma_v(0) = p$ and $\gamma_v(1) = \exp_p(v)$. In particular, if a curve c satisfies $L[c] = |c(0) c(1)|$, then—up to reparameterization— c is a smooth geodesic.

2. *If $q \notin \exp_p(B_r(\mathbf{0})) = B_r(p)$, then there exists $q' \in \partial B_r(p)$ (the boundary of $B_r(p)$) such that*

$$|pq| = r + |q'q|.$$

In particular, $|pq| \geq r$.

I.0.1. PROOF OF LEMMA B.4

The lemma follows quickly from two standard corollaries of the Rauch comparison theorem (Theorem I.2 and Theorem I.3 below). While the lemma is standard, we did not locate a reference that states it in the form we need, so we provide a proof for completeness.

Theorem I.2 ((Cheeger and Ebin, 2008, Corollary 1.35 (“Corollary of Rauch I”)))

Let M_1, M_2 be Riemannian manifolds with $\dim(M_2) \geq \dim(M_1)$. Let $p_1 \in M_1$ and $p_2 \in M_2$. Assume $K_{M_2} \geq K_{M_1}$; i.e., for every plane section σ_1 in M_1 and for every plane section σ_2 in M_2 , we have $K(\sigma_2) \geq K(\sigma_1)$. Let $r > 0$ be such that $\exp_{p_1}|_{B_r(\mathbf{0})}$ is an embedding and $\exp_{p_2}|_{B_r(\mathbf{0})}$ is nonsingular. Let $I : T_{p_1}M_1 \rightarrow T_{p_2}M_2$ be a linear injection preserving inner products. Then for any curve $\gamma : [0, 1] \rightarrow \exp_{p_1}(B_r(\mathbf{0}))$, we have

$$L[\gamma] \geq L[\exp_{p_2} \circ I \circ \exp_{p_1}^{-1}(\gamma)] = L[\gamma_2(t)],$$

where $\gamma_2(t) = \exp_{p_2} \circ I \circ \exp_{p_1}^{-1}(\gamma(t))$ and $L[\cdot]$ denotes the length of a curve in the corresponding manifold.

Theorem I.3 ((Lee, 2018, Theorem 11.12)) *Suppose (M, g) is a Riemannian n -manifold whose sectional curvatures are all bounded above by a constant $\kappa > 0$. Then there is no conjugate point along any geodesic segment shorter than ϖ_κ .*

Proof of Lemma B.4 Given $r \leq r_{\text{inj}}(M)$, the two tangent vectors

$$\hat{x} = \exp_p^{-1}(x), \quad \hat{y} = \exp_p^{-1}(y) \in T_p M$$

are unique and satisfy

$$\|\hat{x}\| = |p x|, \quad \|\hat{y}\| = |p y|.$$

Positive-curvature comparison. Recall that M_κ^d is the simply-connected d -dimensional space of constant curvature $\kappa > 0$. Pick any $p_2 \in M_\kappa^d$ and choose a linear isometry

$$I : T_p M \longrightarrow T_{p_2} M_\kappa^d$$

and set

$$x_2 = \exp_{p_2}(I\hat{x}), \quad y_2 = \exp_{p_2}(I\hat{y}).$$

This is well-defined because I is a linear isometry, and the injectivity radius of M_κ^d is $r_{\text{inj}}(M_\kappa^d) \geq \varpi_\kappa/2 = \pi/(2\sqrt{\kappa})$. Following our notations, we have

$$\hat{x}_2 = (\hat{x}_2)_p = I\hat{x} \quad \text{and} \quad \hat{y}_2 = (\hat{y}_2)_p = I\hat{y}.$$

We have

$$\angle^\kappa(p_2 x_2) = \angle(\hat{x}_2, \hat{y}_2) = \angle(\hat{x}, \hat{y}) := \theta,$$

and

$$|p_2 x_2| = \|\hat{x}_2\| = \|\hat{x}\| = |p x| := a, \quad |p_2 y_2| = \|\hat{y}_2\| = \|\hat{y}\| = |p y| := b.$$

Let γ be the distance-minimizing geodesic from x to y in M .

Claim: $\gamma \subseteq B_r(p)$. Assume for the sake of contradiction that the minimizing geodesic γ from x to y leaves $B_r(p)$. Let $z \in \gamma$ be the first point with $|p z| = r$. Since z lies on the shortest geodesic γ connecting x and y , we have

$$|x y| = |x z| + |z y|.$$

By the triangle inequality,

$$|x z| \geq |p z| - |p x| = r - a, \quad |z y| \geq |p z| - |p y| = r - b,$$

whence

$$|x y| \geq (r - a) + (r - b) > r - \frac{r}{2} + r - \frac{r}{2} = r.$$

But another application of the triangle inequality gives

$$|x y| \leq d(x, p) + |p y| = a + b < \frac{r}{2} + \frac{r}{2} = r,$$

a contradiction. Therefore γ must be contained in $B_r(p)$.

Applying the Rauch comparison theorem. Because $r \leq r_{\text{inj}}(M)$, the restriction $\exp_p|_{B_r(\mathbf{0})}$ is a diffeomorphism. Further, with $r < \varpi_\kappa/2$, we also have $\exp_{p_2}|_{B_r(\mathbf{0})}$ is a diffeomorphism.

Let $\gamma_2 = \exp_{p_2} \circ I \circ \exp_p^{-1}(\gamma)$ be the image of γ under the map I . Applying Theorem I.2 yields

$$|x y| = L[\gamma] \geq L[\gamma_2] \geq |x_2 y_2|.$$

Because $a + b < \varpi_\kappa$, the geodesic triangle $\triangle p_2 x_2 y_2$ exists in M_κ^d , so

$$|x_2 y_2| = \Upsilon^\kappa(\theta; a, b).$$

Consequently,

$$|x y| \geq \Upsilon^\kappa(\theta; a, b),$$

which is exactly the first inequality claimed in (22).

Negative curvature comparison. To obtain the upper bound on $|x y|$ we reverse the roles of M and the model space when we apply Theorem I.2.

Let $M_1 := M_{-\kappa}^d$ and set $M_2 := M$. Choose any point $p_1 \in M_1$ and a linear isometry $I : T_{p_1} M_1 \rightarrow T_p M$. Because I is invertible, put

$$x_1 = \exp_{p_1}(I^{-1}\hat{x}), \quad y_1 = \exp_{p_1}(I^{-1}\hat{y}).$$

and set

$$\theta := \angle^{\kappa_0}(p_1^{x_1}_{y_1}).$$

Similarly to the previous case, we have

$$|p_1 x_1| = \|\hat{x}_1\| = \|\hat{x}\| = |p x| := a, \quad |p_1 y_1| = \|\hat{y}_2\| = \|\hat{y}\| = |p y| := b.$$

Let γ_1 be the minimizing geodesic from x_1 to y_1 in M_1 . By the same argument used earlier (triangle inequalities and the choice of r), $\gamma_1 \subseteq B_r(p_1)$.

For the model space with negative curvature, $\exp_{p_1}$ is a diffeomorphism without restrictions; and $\exp_p|_{B_r(\mathbf{0})}$ for M is a diffeomorphism as well, hence we may apply Theorem I.2 to get

$$|x_1 y_1| = L[\gamma_1] \geq L[\gamma] \geq |x y|.$$

Since the comparison triangle $\triangle p_1 x_1 y_1$ exists (indeed, hyperbolic space admits geodesic triangles of any perimeter), we have

$$|x_1 y_1| = \Upsilon^{\kappa_0}(\theta; a, b),$$

and therefore

$$|x y| \leq \Upsilon^{\kappa_0}(\theta; a, b),$$

which is the second inequality in (22).

From opposite-side to angle comparison. Because $a + b < \varpi_\kappa$, the opposite-side function

$$\alpha \mapsto \Upsilon^\kappa(\alpha; a, b)$$

is smooth and strictly increasing on $(0, \pi)$, with boundary values

$$\Upsilon^\kappa(0; a, b) = |b - a|, \quad \Upsilon^\kappa(\pi; a, b) = a + b.$$

From triangle inequality also have $|b - a| < |x y| < a + b$, so by strict monotonicity there is a unique $\alpha_1 \in (0, \pi)$ satisfying

$$\Upsilon^\kappa(\alpha_1; a, b) = |x y|.$$

By construction this α_1 is the model-space angle:

$$\alpha_1 = \angle^\kappa(p_y^x).$$

Because $\gamma^\kappa(\cdot; a, b)$ is increasing and $\gamma^\kappa(\alpha_1; a, b) = |xy| \geq \gamma^\kappa(\angle(p_y^x); a, b)$, we must have

$$\angle^\kappa(p_y^x) = \alpha_1 \geq \angle(p_y^x),$$

which yields the second inequality in (23).

The first inequality is obtained in exactly the same way, replacing the positive curvature model space M_κ by the lower-curvature model space $M_{-\kappa}$ and using the inequality in the opposite direction. $\blacksquare$

I.0.2. QUANTITATIVE ESTIMATES OF OPPOSITE SIDE LENGTH WITH 1 SMALL ADJACENT SIDE

Proof of Lemma B.6

First, we apply the triangle comparison lemma (Lemma B.4) to the triangle $\triangle pqx$ in M . Comparing simultaneously with the positively curved model space M_κ and the negatively curved model space $M_{-\kappa}$ yields

$$\gamma^\kappa(\angle(p_q^x); |px|, |pq|) \leq |qx| \leq \gamma^{-\kappa}(\angle(p_q^x); |px|, |pq|).$$

The rest of the proof follows by estimating the opposite side lengths in the two model spaces, which was stated in Lemma I.5 and Lemma I.6. $\blacksquare$

Corollary I.4 *With the same assumptions as in Lemma B.6, we have*

$$|a - c - b \cos(\theta)| \leq 4 \frac{b^2}{a}.$$

Proof Given the assumptions on a and b ,

$$\frac{\kappa b^2}{3} = \frac{\kappa a^2}{3} \frac{b^2}{a^2} \leq \frac{1}{16} \frac{1}{3} \frac{b}{a}.$$

Together with $|\cos(\theta)| \leq 1$, the estimate follows immediately. $\blacksquare$

Lemma I.5 *Fix $\kappa > 0$ and consider a geodesic triangle in M_κ whose two adjacent sides have lengths a and b . Assume*

$$0 < a, b < \frac{1}{2} \varpi_\kappa \quad \text{and} \quad b \leq \frac{1}{4} a.$$

Let $\theta \in [0, \pi]$ be the angle between the two sides of lengths a and b at the vertex opposite to the side of length $c = \gamma^{-\kappa}(\theta; a, b)$. Then

$$a - c - b \cos \theta \leq \pi \frac{b}{a} \cdot b |\cos \theta|.$$

Proof Throughout, write

$$c := \Upsilon^\kappa(\theta; a, b),$$

where $\Upsilon^\kappa(\theta; a, b)$ denotes—by definition—the length of the side opposite the angle θ in a geodesic triangle of M_κ whose adjacent sides have lengths a and b .

Normalized variables and cosine law. Set

$$\tilde{a} := \sqrt{\kappa} a, \quad \tilde{b} := \sqrt{\kappa} b, \quad \tilde{c} := \sqrt{\kappa} c.$$

From the spherical law of cosines in M_κ (see (24)), we have $\tilde{a}, \tilde{b}, \tilde{c}$ and θ satisfies spherical law of cosines on the unit sphere M_1 :

$$\cos \tilde{c} = \cos \tilde{a} \cos \tilde{b} + \sin \tilde{a} \sin \tilde{b} \cos \theta. \quad (67)$$

Define

$$\Delta := \cos \tilde{a} (\cos \tilde{b} - 1) + \sin \tilde{a} \sin \tilde{b} \cos \theta,$$

so that (67) is $\cos \tilde{c} = \cos \tilde{a} + \Delta$. By the fundamental theorem of calculus,

$$\tilde{c} = \arccos(\cos \tilde{a} + \Delta) = \tilde{a} - \int_{\cos \tilde{a}}^{\cos \tilde{a} + \Delta} \frac{1}{\sqrt{1 - s^2}} ds. \quad (68)$$

Case $\theta \in [0, \pi/2]$. Here $\cos \theta \geq 0$.

If $\Delta \leq 0$, then $\cos \tilde{c} \leq \cos \tilde{a}$ and hence $\tilde{c} \geq \tilde{a}$, whence $\tilde{a} - \tilde{c} - \tilde{b} \cos \theta \leq 0$, which already implies the desired bound. Now we assume $\Delta > 0$. For $s \in [\cos \tilde{a}, \cos \tilde{c}] \subset (0, 1)$ we have

$$\frac{1}{\sqrt{1 - s^2}} \leq \frac{1}{\sin \tilde{c}} \leq \frac{1}{\sin(\tilde{a} - \tilde{b})},$$

because $\tilde{c} \geq \tilde{a} - \tilde{b}$ and $\sin$ is increasing on $[0, \pi/2]$. Since $\cos t$ decreases on $[0, \pi/2]$,

$$\sin \tilde{a} - \sin(\tilde{a} - \tilde{b}) = \int_{\tilde{a} - \tilde{b}}^{\tilde{a}} \cos t dt \leq \int_0^{\tilde{b}} \cos t dt = \sin \tilde{b},$$

so $\sin(\tilde{a} - \tilde{b}) \geq \sin \tilde{a} - \sin \tilde{b}$. Combining these bounds yields

$$\tilde{c} \geq \tilde{a} - \frac{\Delta}{\sin \tilde{a} - \sin \tilde{b}} \geq \tilde{a} - \frac{\sin \tilde{a}}{\sin \tilde{a} - \sin \tilde{b}} \sin \tilde{b} \cos \theta.$$

Because $0 < \tilde{b} \leq \tilde{a}/4 < \pi/8$, $\sin \tilde{b}/\sin \tilde{a} \leq \frac{1}{2}$, and for $t \in [0, 1/2)$ we have $(1 - t)^{-1} \leq 1 + 2t$. Hence

$$\frac{\sin \tilde{a}}{\sin \tilde{a} - \sin \tilde{b}} \leq 1 + 2 \frac{\sin \tilde{b}}{\sin \tilde{a}},$$

so that

$$\tilde{c} \geq \tilde{a} - \sin \tilde{b} \cos \theta - 2 \frac{\sin^2 \tilde{b}}{\sin \tilde{a}} \cos \theta \geq \tilde{a} - \tilde{b} \cos \theta - \pi \frac{\tilde{b}^2}{\tilde{a}} \cos \theta,$$

where we used $\sin \tilde{b} \leq \tilde{b}$ and $\sin \tilde{a} \geq \frac{\pi}{2} \tilde{a}$. Rewriting, we obtain

$$\tilde{a} - \tilde{c} - \tilde{b} \cos \theta \leq \pi \frac{\tilde{b}}{\tilde{a}} \tilde{b} |\cos \theta| \iff a - c - b \cos \theta \leq \pi \frac{b}{a} b |\cos \theta|.$$

Case $\theta \in (\pi/2, \pi]$. Now $\cos \theta \leq 0$. Note that

$$\Delta = \underbrace{\cos \tilde{a}(\cos \tilde{b} - 1)}_{\leq 0} + \underbrace{\sin \tilde{a} \sin \tilde{b} \cos \theta}_{\leq 0} \leq 0, \quad |\Delta| \geq -\sin \tilde{a} \sin \tilde{b} \cos \theta.$$

Reversing the limits in (68),

$$\tilde{c} = \tilde{a} + \int_{\cos \tilde{a} + \Delta}^{\cos \tilde{a}} \frac{1}{\sqrt{1-s^2}} ds \geq \tilde{a} + \frac{|\Delta|}{\sin \tilde{a}} \geq \tilde{a} - \sin \tilde{b} \cos \theta.$$

Because $0 < \tilde{b} \leq \pi/8 < 1/2$, the alternating series for $\sin$ yields $\sin \tilde{b} \geq \tilde{b} - \tilde{b}^3/6$. Hence

$$\tilde{c} \geq \tilde{a} - \tilde{b} \cos \theta + \frac{\tilde{b}^3}{6} \cos \theta, \quad \implies \quad a - c - b \cos \theta \leq \frac{\kappa b^2}{6} b |\cos \theta|.$$

Finally, since $b \leq a/4$ and $a < \varpi_\kappa/2 = \pi/(2\sqrt{\kappa})$,

$$\frac{\kappa b^2}{6} \leq \pi \frac{b}{a},$$

so the claimed inequality follows. ■

Lemma I.6 *Fix $\kappa > 0$ and consider a geodesic triangle in $M_{-\kappa}$ whose two adjacent sides have lengths a and b satisfying*

$$0 < a, b < \frac{1}{\sqrt{\kappa}}.$$

Let $\theta \in [0, \pi]$ be the angle between the two sides of lengths a and b at the vertex opposite to the side of length $c = \Upsilon^{-\kappa}(\theta; a, b)$. Then

$$a - c - b \cos(\theta) \geq -\frac{7}{6} \frac{b^2}{a} - \frac{\kappa b^2}{3} \cdot b |\cos(\theta)|.$$

Proof The proof in the hyperbolic case is indeed similar, thanks to the hyperbolic law of cosines (25):

$$\cosh(\sqrt{\kappa}c) = \cosh(\sqrt{\kappa}a) \cosh(\sqrt{\kappa}b) - \sinh(\sqrt{\kappa}a) \sinh(\sqrt{\kappa}b) \cos(\theta).$$

Again, let us write

$$\tilde{a} = \sqrt{\kappa}a, \quad \tilde{b} = \sqrt{\kappa}b, \quad \tilde{c} = \sqrt{\kappa}c.$$

Recalling that

$$\cosh(x) = \frac{e^x + e^{-x}}{2} \quad \text{and} \quad \sinh(x) = \frac{e^x - e^{-x}}{2}.$$

Let us write

$$\Delta = \tilde{c} - \tilde{a}.$$

Given $\cosh(t)$ is concave up with derivative $\sinh(t)$, we have

$$\cosh(\tilde{c}) \geq \cosh(\tilde{a}) + \sinh(\tilde{a})\Delta,$$

which implies

$$\Delta \leq \frac{\cosh(\tilde{a})}{\sinh(\tilde{a})} (\cosh(\tilde{b}) - 1) - \sinh(\tilde{b}) \cos(\theta). \quad (69)$$

Estimate $\sinh$ and $\cosh$ by comparing their Taylor series with Geometric series. Recall the Taylor series of $\sinh$ and $\cosh$ at 0:

$$\begin{aligned} \sinh(x) &= \sum_{n=0}^{\infty} \frac{x^{2n+1}}{(2n+1)!} = x + \frac{x^3}{6} + \frac{x^5}{120} + \cdots, \\ \cosh(x) &= \sum_{n=0}^{\infty} \frac{x^{2n}}{(2n)!} = 1 + \frac{x^2}{2} + \frac{x^4}{24} + \cdots. \end{aligned}$$

When $x \in [0, 1]$, both series converges faster than a geometric series with a rate $1/2$, so we can use the following estimates:

$$\forall x \in [0, 1] : \quad x \leq \sinh(x) \leq x + \frac{x^3}{3} \leq \frac{4}{3}x \quad \text{and} \quad \cosh(x) \leq 1 + \frac{x^2}{2} + \frac{x^4}{12} \leq 1 + \frac{7}{12}x^2. \quad (70)$$

Estimate Δ . The first term in the right-hand side of (69) can be estimated as follows.

$$\frac{\cosh(\tilde{a})}{\sinh(\tilde{a})} (\cosh(\tilde{b}) - 1) \leq \frac{2}{\tilde{a}} \frac{7}{12} \tilde{b}^2 = \frac{7}{6} \frac{\tilde{b}^2}{\tilde{a}}.$$

The second term can be estimated depending on the sign of $\cos(\theta)$. When $\theta \in [0, \pi/2]$, we have $\cos(\theta) \geq 0$ and thus we can rely on the simple bound $\sinh(\tilde{b}) \geq \tilde{b}$ to get

$$-\sinh(\tilde{b}) \cos(\theta) \leq -\tilde{b} \cos(\theta).$$

This gives us the estimate

$$\tilde{c} - \tilde{a} \leq \frac{7}{6} \frac{\tilde{b}^2}{\tilde{a}} - \tilde{b} \cos(\theta) \quad \Leftrightarrow \quad a - c - b \cos(\theta) \geq -\frac{7}{6} \frac{b^2}{a}.$$

As for $\theta \in (\pi/2, \pi]$ where $\cos(\theta) < 0$, we invoke (70) to get

$$-\sinh(\tilde{b}) \cos(\theta) \leq -\tilde{b} \cos(\theta) - \frac{\tilde{b}^3}{3} \cos(\theta).$$

This gives us the estimate

$$\tilde{c} - \tilde{a} \leq \frac{7}{6} \frac{\tilde{b}^2}{\tilde{a}} - \tilde{b} \cos(\theta) - \frac{\tilde{b}^3}{3} \cos(\theta) \quad \Leftrightarrow \quad a - c - b \cos(\theta) \geq -\frac{7}{6} \frac{b^2}{a} - \frac{\kappa b^2}{3} \cdot b |\cos(\theta)|.$$

■

I.0.3. SPHERICAL ANGLE ESTIMATE VIA SIDE RATIO

Proof of Lemma B.8

We can assume $\kappa = 1$ without loss of generality.

Spherical law of cosines and Taylor expansion. Recall the spherical law of cosines in the model space M_1 :

$$\cos c = \cos a \cos b + \sin a \sin b \cos \theta$$

For the right hand side, we apply $\cos(a+b) = \cos a \cos b - \sin a \sin b$ to get

$$\cos a \cos b + \sin a \sin b \cos \theta = \cos(a+b) - \sin a \sin b(1 - \cos \theta) \leq 1 - \sin a \sin b(1 - \cos \theta).$$

Since $c \leq \frac{1}{2}a$, the triangle inequality yields $b \geq a - c \geq \frac{1}{2}a$. Together with the assumption that $a \leq \frac{\pi}{4}$ and using

$$\sin(t) \geq \frac{1}{\sqrt{2}} \frac{4}{\pi} t \quad t \in [0, \pi/4],$$

we obtain

$$1 - \sin a \sin b(1 - \cos \theta) \leq 1 - \frac{8}{\pi^2} \cdot \frac{1}{2} a^2 (1 - \cos \theta).$$

On the other hand, the standard estimate for the cosine function gives the bound on the left hand side of the spherical law of cosines:

$$\cos c \geq 1 - \frac{1}{2} c^2.$$

Substituting the two inequalities into the spherical law of cosines yields

$$\begin{aligned} 1 - \frac{1}{2} c^2 &\leq 1 - \frac{1}{2} \frac{8}{\pi^2} a^2 (1 - \cos \theta) \\ \Rightarrow \quad c &\geq \frac{\sqrt{8}}{\pi} a \sqrt{1 - \cos(\theta)}. \end{aligned} \tag{71}$$

Claim: $\theta \leq \pi/3$. Substituting the assumption $c \leq \frac{1}{2}a$ into the above inequality (71) gives

$$\frac{1}{2} \geq \frac{\sqrt{8}}{\pi} \sqrt{1 - \cos(\theta)}.$$

Assume, for contradiction, that $\theta \geq \pi/3$. Then,

$$\frac{\sqrt{8}}{\pi} \sqrt{1 - \cos(\theta)} \geq \frac{2}{\pi} > \frac{1}{2}.$$

This contradicts the above inequality, hence we conclude that $\theta < \pi/3$.

Bounding $\cos(\theta)$ from below on $[0, \pi/3]$. We claim that

$$\cos x \leq 1 - \frac{1}{2} \left(\frac{3x}{\pi} \right)^2, \quad \forall x \in [0, \pi/3]. \tag{72}$$

Equivalently, set

$$F(x) := 1 - \frac{1}{2} \left(\frac{3x}{\pi} \right)^2 - \cos x, \quad x \in [0, \pi/3],$$

and show $F(x) \geq 0$ on this interval. First, a direct computation gives $F(0) = F(\pi/3) = 0$. Now consider its derivative

$$F'(x) = -\frac{9}{\pi^2} x + \sin x.$$

We remark that F' has the same sign as

$$G(x) := \frac{F'(x)}{x} = -\frac{9}{\pi^2} + \frac{\sin x}{x}, \quad x \in (0, \pi/3].$$

on $(0, \pi/3]$. Because $x \mapsto \sin x/x$ is strictly decreasing on $(0, \pi/2)$, G is strictly decreasing on $(0, \pi/3]$. Moreover,

$$\lim_{x \rightarrow 0^+} G(x) = 1 > 0, \quad G(\pi/3) = -\frac{9}{\pi^2} + \frac{3 \sin(\pi/3)}{\pi} < 0.$$

Hence there exists a unique $x_0 \in (0, \pi/3)$ such that $G(x_0) = 0$, i.e. $F'(x_0) = 0$. Because G changes sign from positive to negative at x_0 , we have

$$F'(x) \begin{cases} > 0, & x \in [0, x_0), \\ < 0, & x \in (x_0, \pi/3], \end{cases}$$

so F attains its unique local (and global) maximum at x_0 . Since F vanishes at both endpoints and is non-negative at its single interior extremum, it follows that $F(x) \geq 0$ for all $x \in [0, \pi/3]$, proving (72).

Conclusion. With our claim that $\theta \leq \pi/3$, we can substitute the above bound on $\cos(x)$ into (71) to obtain

$$c \geq \frac{\sqrt{8}}{\pi} a \sqrt{\frac{1}{2} \left(\frac{3}{\pi} \theta \right)^2} \quad \Rightarrow \quad \frac{c}{a} \geq \frac{6}{\pi^2} \theta \geq \frac{1}{2} \theta.$$

■

I.0.4. OPPOSITE SIDE ESTIMATES WITH ERROR IN TERMS OF MAXIMAL SIDE LENGTH

Lemma I.7 *Let (M, g) be a Riemannian manifold whose sectional curvatures are uniformly bounded in absolute value by a constant $\kappa > 0$. Suppose p, x, y be points in M such that*

$$0 < |px|, |py| < \frac{1}{8} \min\{\varpi_\kappa, r_{\text{inj}}(M)\}.$$

Let $\theta = \angle(p_y^x) \in [0, \pi]$. Then, the following holds:

$$\left| |xy|^2 - (|px|^2 + |py|^2 - 2|px||py|\cos(\theta)) \right| \leq 2\kappa \max\{|px|^4, |py|^4\}. \quad (73)$$

Proof Without lose of generality, we can assume that

$$|p x| \geq |p y|.$$

We first invoke Lemma B.4 to get

$$\Upsilon^\kappa(\theta; |p x|, |p y|) \leq |x y| \leq \Upsilon^{-\kappa}(\theta; |p x|, |p y|).$$

Now, we will bound the opposite sides in the two cases using the spherical and hyperbolic law of cosines, respectively.

Spherical Cosine Law. Let $a = \sqrt{\kappa}|p x|$, $b = \sqrt{\kappa}|p y|$, and $c = \sqrt{\kappa} \Upsilon^\kappa(\theta; |p x|, |p y|)$. In particular, we have $b \leq a \leq 1$. The spherical law of cosines in the model space M_κ states

$$\cos c = \cos a \cos b + \sin a \sin b \cos \theta.$$

For $0 \leq x \leq \pi/4 < 1$, the Taylor expansion of $\cos x$ and $\sin x$ together with the alternating-series remainder give

$$1 - x^2/2 \leq \cos x \leq 1 - x^2/2 + x^4/24, \quad \text{and} \quad x - \frac{x^3}{6} \leq \sin x \leq x.$$

Hence, for $a, b \in [0, \pi/8]$, we have

$$1 - c^2/2 \leq \cos c.$$

Using the upper bound for $\cos$ and the fact that $b \leq a \leq 1$,

$$\begin{aligned} \cos a \cos b &\leq \left(1 - \frac{a^2}{2} + \frac{a^4}{24}\right) \left(1 - \frac{b^2}{2} + \frac{b^4}{24}\right) \\ &= 1 - \frac{a^2}{2} - \frac{b^2}{2} + \frac{a^2 b^2}{4} + \left(1 - \frac{a^2}{2}\right) \frac{b^4}{24} + \left(1 - \frac{b^2}{2}\right) \frac{a^4}{24} + \frac{a^4 b^4}{24 \cdot 24} \\ &\leq 1 - \frac{a^2}{2} - \frac{b^2}{2} + a^4 \left(\frac{1}{4} + 2 \cdot \frac{1}{24} + \frac{1}{(24)^2}\right) \\ &= 1 - \frac{a^2}{2} - \frac{b^2}{2} + \frac{a^4}{2}. \end{aligned}$$

Because $\cos(\theta)$ may be negative, we combine the upper and lower Taylor bounds for $\sin$:

$$\sin(a) \sin(b) \cos(\theta) \leq ab \cos \theta + \frac{ab^3}{12} + \frac{a^3 b}{12} + \frac{a^3 b^3}{36} \leq ab \cos \theta + \frac{7}{36} a^4,$$

again using $b \leq a$. Collecting the above bounds and substituting into the spherical law of cosines gives

$$1 - \frac{c^2}{2} \leq 1 - \frac{a^2}{2} - \frac{b^2}{2} + \frac{a^4}{2} + ab \cos(\theta) + \frac{7}{36} a^4.$$

which simplifies to

$$c^2 \geq a^2 + b^2 - 2ab \cos(\theta) - 2a^4.$$

Rewriting in the original variables yields

$$\Upsilon^\kappa(\theta; |p x|, |p y|)^2 \geq |p x|^2 + |p y|^2 - 2|p x||p y| \cos(\theta) - 2\kappa|p x|^4.$$

Hyperbolic Cosine Law. Similar, let $a = \sqrt{\kappa}|p x|$, $b = \sqrt{\kappa}|p y|$, and $c = \sqrt{\kappa}\Upsilon^{-\kappa}(\theta; |p x|, |p y|)$. The hyperbolic law of cosines in the model space $M_{-\kappa}$ states

$$\cosh c = \cosh a \cosh b - \sinh a \sinh b \cos \theta.$$

For every $x \geq 0$,

$$\cosh x = 1 + \frac{1}{2}x^2 + \sum_{k=2}^{\infty} \frac{x^{2k}}{(2k)!} \geq 1 + \frac{1}{2}x^2, \quad \implies \quad \cosh c \geq 1 + \frac{1}{2}c^2.$$

For $0 \leq x \leq \pi/4 < 1$,

$$\cosh x = 1 + \frac{x^2}{2} + \sum_{k=2}^{\infty} \frac{x^{2k}}{(2k)!} \leq 1 + \frac{x^2}{2} + \frac{x^4}{24} \left(\sum_{s=0}^{\infty} \left(\frac{1}{5 \cdot 6} \right)^s \right) = 1 + \frac{x^2}{2} + \frac{x^4}{24} \cdot \frac{30}{29} \leq 1 + \frac{x^2}{2} + \frac{x^4}{23}.$$

so that

$$\begin{aligned} \cosh a \cosh b &\leq \left(1 + \frac{a^2}{2} + \frac{a^4}{23} \right) \left(1 + \frac{b^2}{2} + \frac{b^4}{23} \right) \\ &\leq 1 + \frac{a^2}{2} + \frac{b^2}{2} + \frac{a^4}{2}, \end{aligned}$$

where the inequality follows from expanding the product and using $b \leq a \leq 1$.

For the second term on the right hand side, for the same reason that $\cos(\theta)$ can be negative. For $0 \leq x \leq \pi/4 < 1$,

$$\begin{aligned} |\sinh(x) - x| &= \sum_{k=1}^{\infty} \frac{x^{2k+1}}{(2k+1)!} \leq \frac{x^3}{3!} \sum_{s=0}^{\infty} \left(\frac{1}{4 \cdot 5} \right)^s = \frac{x^3}{6} \frac{20}{19} \leq \frac{x^3}{5} \\ \implies |\sinh(a) \sinh(b) \cos(\theta) - ab \cos(\theta)| &\leq \frac{ab^3 + ba^3}{5} + \frac{a^3 b^3}{25} \leq \frac{6}{25} a^4. \end{aligned}$$

Combining the above estimates, we have

$$c^2 \leq a^2 + b^2 - ab \cos(\theta) + 2a^4,$$

or equivalently,

$$\Upsilon^{-\kappa}(\theta; |p x|, |p y|)^2 \leq |p x|^2 + |p y|^2 - 2|p x||p y| \cos(\theta) + 2\kappa|p x|^4.$$

■

Appendix J. Lower Bounds with a Sequence of Bumps

This section discusses the lower bounds for errors of approximating distances from random geometric graphs. We are going to construct two manifolds which are “very close” in the sense that our random geometric graph model, with high probability, cannot distinguish them; on the other hand, the two manifolds are sufficiently different, and so this gives a lower bound for errors of distance estimation.

More precisely, we are going to construct (M_1, g_1, μ_1) and (M_2, g_2, μ_2) and a coupling π of

$$G_1 \sim G(n, M_1, g_1, \mu_1, p, s_n = 1) \quad \text{and} \quad G_2 \sim G(n, M_2, g_2, \mu_2, p, s_n = 1),$$

so that asymptotically the random geometric graph model cannot distinguish G_1 and G_2 . We are going to determine two special points X, Y so that $|XY|_{g_1}$ and $|XY|_{g_2}$ are sufficiently different.

What does our construction show? The upshot of our construction is we are going to *disprove* the following statement: there exists an algorithm which takes the random geometric graph as input and with high probability produces the intrinsic distances of all pairs of latent points simultaneously with the uniform error bound $\lesssim n^{-4/d}$ (up to polylogarithmic factors). Since we can couple the two manifolds so that the resulting random geometric graphs from the two models are the same graph with high probability, we know that the algorithm would output the same distance estimates with high probability. However, since the two manifolds are different, our calculation below shows that one of the two applications of the algorithm must have too much error.

J.1. Parameters

Let $d \geq 2$ be a positive integer representing the dimension of the manifolds. As point sets, let both M_1 and M_2 be the torus $\mathbb{T}^d := \mathbb{R}^d / \mathbb{Z}^d$. Let the metric g_1 on M_1 be the flat metric according to the measure induced from the usual Lebesgue measure on $\mathbb{R}^d$, so M_1 becomes a flat torus.

The positive integer $n \in \mathbb{Z}_{\geq 1}$ is to represent the number of latent points. We assume n to be large. At the very least, we require $n \geq 100$.

Let $\kappa > 0$ be a positive real number representing the two-sided sectional curvature bound. The two manifolds M_1 and M_2 are to be constructed in a way that the sectional curvature everywhere on M_1 and M_2 is always in $(-\kappa, \kappa)$.

Now let us consider $C_1(d) := \sqrt{d} + 7$. Cheeger’s theorem and Klingenberg’s lemma together imply that there exists a constant $c_2(d, \kappa) > 0$, depending only on d and κ , such that for every d -dimensional manifold N with $\text{diam}(N) \leq C_1(d)$, $\text{vol}(N) \geq 1$, and $K_N \geq -\kappa$, we have $r_{\text{inj}}(N) > c_2(d, \kappa) > 0$.

We define

$$\lambda = \lambda(d, \kappa) := 2^{-5} \cdot \min \left\{ 1, c_2(d, \kappa), \frac{\pi}{\sqrt{\kappa}} \right\} > 0.$$

Next, we define

$$r_{\text{bump}} := 0.01 \cdot \lambda \cdot n^{-2/d} \cdot (\log n)^{-1/2},$$

to represent the “radius of a small bump”, the meaning of which should be clear in what follows, and define

$$N_{\text{bump}} := \left\lceil \frac{\lambda}{2r_{\text{bump}}} \right\rceil,$$

to represent the “number of small bumps”.

On both manifolds M_1 and M_2 , we define $X = (-2\lambda, 0, \dots, 0)$ and $Y := (2\lambda, 0, \dots, 0)$. Let $Z_1, Z_2, \dots, Z_{N_{\text{bump}}}$ be points on the g_1 -geodesic segment connecting X and Y , spaced so that

$$|X Z_1|_{g_1} = |Z_{N_{\text{bump}}} Y|_{g_1} = \lambda$$

and

$$|Z_1 Z_2|_{g_1} = |Z_2 Z_3|_{g_1} = \dots = |Z_{N_{\text{bump}}-1} Z_{N_{\text{bump}}}|_{g_1} = \frac{2\lambda}{N_{\text{bump}} - 1}.$$

Define

$$m := \frac{\log n}{n}.$$

The probability measures μ_1 and μ_2 on M_1 and M_2 are given by $(1 - 2m)$ times the uniform measure on $\mathbb{R}^d/\mathbb{Z}^d$ induced from the standard Euclidean measure plus m times a Dirac measure at X plus m times a Dirac measure at Y .

J.2. Conformal changes to the metric

By using conformal changes to the metric, we create a small bump centered at each Z_i with radius r_{bump} . This construction gives a metric g_2 on M_2 . Note that the parameter assumptions above guarantee that the bumps do not overlap.

Let us now describe the construction of each bump. For convenience, let us simply describe construction a bump centered at $\mathbf{0}$. The actual bumps can be obtained by translating this bump to each center Z_i .

We use the usual coordinates $x^1, x^2, \dots, x^d$ in a coordinate chart near $\mathbf{0}$ that contains $B(\mathbf{0}, 0.03)$. With these coordinates, the original flat metric $g_1 = (dx^1)^2 + (dx^2)^2 + \dots + (dx^d)^2$ has the matrix representation

$$g_1 = I_d \in \mathbb{R}^{d \times d}.$$

While we use the rectangular coordinates, it is helpful to consider $r := \sqrt{(x^1)^2 + \dots + (x^d)^2}$. For a smooth function $h : [0, 0.03) \rightarrow \mathbb{R}_{>0}$ to be determined, we define the modified metric g_2 via the radially-symmetric conformal change

$$g_2(p) = f(p) \cdot g_1(p) = h(\|p\|) \cdot g_1(p),$$

for every point p on this coordinate chart so that for every $r \geq r_{\text{bump}}$, we have $h(r) = 1$. This last condition guarantees that g_1 and g_2 agree everywhere outside of the small bump. In matrix form, $g_2 = f(p) \cdot I_d = h(r) \cdot I_d$. Following the usual convention, let us write $f(p) := e^{2\varphi(p)}$. Let us also write $h(r) = e^{2\psi(r)}$, where $\psi : [0, 0.03) \rightarrow \mathbb{R}$ so that $\psi(r) = 0$ for every $r \geq r_{\text{bump}}$. This is saying that both f and φ factor through the norm function.

J.2.1. UPPER BOUND ON SECTIONAL CURVATURE IN M_1

Consider an arbitrary point $p \in B(\mathbf{0}, r_{\text{bump}}) \subseteq \mathbb{T}^d$. Consider two arbitrary nonparallel tangent vectors $u = u^i \partial_i, v = v^j \partial_j \in T_p M_2$. The sectional curvature for the plane spanned by u and v is given by

$$K(u, v) := \frac{g_2(R(u, v)v, u)}{g_2(u, u)g_2(v, v) - g_2(u, v)^2} = \frac{1}{f(p)} \cdot \frac{g_1(R(u, v)v, u)}{g_1(u, u)g_1(v, v) - g_1(u, v)^2},$$

where R is the Riemann curvature tensor on M_2 (with respect to g_2). If we take u and v to be an orthonormal basis of the plane (with respect to g_1), then the sectional curvature simplifies to

$$K(u, v) = \frac{1}{f(p)} \cdot g_1(R(u, v)v, u) = \frac{g_2(R(u, v)v, u)}{f(p)^2}.$$

Let us recall the following formula for Christoffel symbols (with respect to the metric g_2):

$$\begin{aligned} \Gamma_{k\ell}^i &= \frac{1}{2} g^{im} \left(\frac{\partial g_{mk}}{\partial x^\ell} + \frac{\partial g_{m\ell}}{\partial x^k} - \frac{\partial g_{k\ell}}{\partial x^m} \right) \\ &= \frac{1}{2 \cdot f(p)} \cdot \left(\frac{\partial f(p)}{\partial x^\ell} \cdot \mathbf{1}_{i=k} + \frac{\partial f(p)}{\partial x^k} \cdot \mathbf{1}_{i=\ell} - \frac{\partial f(p)}{\partial x^i} \cdot \mathbf{1}_{k=\ell} \right). \end{aligned}$$

Since $f(p) = e^{2\varphi(p)}$, the chain rule gives

$$\Gamma_{k\ell}^i = \varphi_\ell \delta_{ik} + \varphi_k \delta_{i\ell} - \varphi_i \delta_{k\ell},$$

where $\varphi_i = \partial_i \varphi = \partial \varphi / \partial x^i$, and δ_{ij} denotes the Kronecker delta $\mathbf{1}_{i=j}$.

Following Petersen ([Petersen, 2016](#), §§ 3.1.6), we have the following formula for the $(1, 3)$ -Riemann curvature tensor (with respect to g_2):

$$g_2(R(\partial_i, \partial_j)\partial_k, \partial_\ell) = R_{ijk}^\ell = \partial_i \Gamma_{jk}^\ell - \partial_j \Gamma_{ik}^\ell + \Gamma_{jk}^s \Gamma_{is}^\ell - \Gamma_{ik}^s \Gamma_{js}^\ell.$$

So we have that

$$\begin{aligned} R_{ijk}^\ell &= (\varphi_{ik} - \varphi_i \varphi_k) \delta_{j\ell} + (\varphi_{j\ell} - \varphi_j \varphi_\ell) \delta_{ik} - (\varphi_{i\ell} - \varphi_i \varphi_\ell) \delta_{jk} - (\varphi_{jk} - \varphi_j \varphi_k) \delta_{i\ell} \\ &\quad + (\delta_{ik} \delta_{j\ell} - \delta_{jk} \delta_{i\ell}) \|\nabla \varphi\|^2. \end{aligned}$$

Here, the function φ_{ij} denotes $\partial_i \varphi_j = \partial_i \partial_j \varphi$, and

$$\|\nabla \varphi\|^2 = \sum_s \varphi_s^2.$$

Since

$$K(u, v) = \frac{1}{f(p)^2} \sum_{i,j,k,\ell} u^i v^j v^k u^\ell R_{ijk}^\ell,$$

we obtain the following formula for orthonormal $u = \sum_i u^i \partial_i$ and $v = \sum_j v^j \partial_j$:

$$-f(p)^2 \cdot K(u, v) = \sum_{i,j} (u^i u^j + v^i v^j) (\varphi_{ij} - \varphi_i \varphi_j) + \|\nabla \varphi\|^2.$$

Now we use radial symmetry. Recall that

$$f(p) = h(\|p\|) = h(r) \quad \text{and} \quad \varphi(p) = \psi(\|p\|) = \psi(r).$$

By the chain rule, we find

$$\|(\nabla \varphi)(p)\|^2 = (\psi'(r))^2.$$

Note that for any $i \in [d]$, we have

$$\varphi_i(p) = \psi'(r) \cdot \frac{x^i}{r},$$

which implies, for any $i, j \in [d]$,

$$\varphi_i \varphi_j = \frac{\psi'(r)^2}{r^2} \cdot x^i x^j,$$

and

$$\varphi_{ij} = \frac{\psi''(r)}{r^2} \cdot x^i x^j - \frac{\psi'(r)}{r^3} \cdot x^i x^j + \frac{\psi'(r)}{r} \cdot \delta_{ij}.$$

Hence, for any $i, j \in [d]$, we have

$$\varphi_{ij} - \varphi_i \varphi_j = \zeta(r) \cdot x^i x^j + \frac{\psi'(r)}{r} \delta_{ij},$$

where

$$\zeta(r) := \frac{\psi''(r)}{r^2} - \frac{\psi'(r)^2}{r^2} - \frac{\psi'(r)}{r^3}.$$

This implies the following simple formula for sectional curvatures:

$$-f(p)^2 \cdot K(u, v) = \zeta(r) \left(\sum_i u^i x^i \right)^2 + \zeta(r) \left(\sum_i v^i x^i \right)^2 + 2 \frac{\psi'(r)}{r} + \psi'(r)^2.$$

Lemma J.1 *Let $u^1, \dots, u^d, v^1, \dots, v^d$ be real numbers such that*

$$\sum_i (u^i)^2 = \sum_i (v^i)^2 = 1 \quad \text{and} \quad \sum_i u^i v^i = 0.$$

For any real numbers $x^1, \dots, x^d$, we have

$$\left(\sum_i u^i x^i \right)^2 + \left(\sum_i v^i x^i \right)^2 \leq \sum_i (x^i)^2.$$

Proof Consider the usual $\mathbb{R}^d$ with the usual Euclidean norm $\|\cdot\|$ and Euclidean metric $\langle \cdot, \cdot \rangle$. Write $\mathbf{x} := (x^1, \dots, x^d)$, $\mathbf{u} := (u^1, \dots, u^d)$, and $\mathbf{v} := (v^1, \dots, v^d)$. Note that $\mathbf{u}$ and $\mathbf{v}$ are orthonormal vectors. Therefore, we can write

$$\mathbf{x} = \langle \mathbf{x}, \mathbf{u} \rangle \cdot \mathbf{u} + \langle \mathbf{x}, \mathbf{v} \rangle \cdot \mathbf{v} + \mathbf{y},$$

where the three summands are pairwise orthogonal. Thus,

$$\|\mathbf{x}\|^2 = \langle \mathbf{x}, \mathbf{u} \rangle^1 + \langle \mathbf{x}, \mathbf{v} \rangle^2 + \|\mathbf{y}\|^2 \geq \langle \mathbf{x}, \mathbf{u} \rangle^1 + \langle \mathbf{x}, \mathbf{v} \rangle^2,$$

which is the desired inequality. ■

Combining the lemma and the formula above, we obtain the following bound:

$$f(p)^2 \cdot |K(u, v)| \leq \max \left\{ \left| 2 \cdot \frac{\psi'(r)}{r} + \psi'(r)^2 \right|, \left| \psi''(r) + \frac{\psi'(r)}{r} \right| \right\},$$

which gives

$$|K(u, v)| \leq e^{-4\psi(r)} \max \left\{ \left| 2 \cdot \frac{\psi'(r)}{r} + \psi'(r)^2 \right|, \left| \psi''(r) + \frac{\psi'(r)}{r} \right| \right\},$$

By the triangle inequality, the following proposition is immediate.

Proposition J.2 *In the above notations, the magnitude of the sectional curvature K is bounded above as follows.*

$$|K| \leq 3e^{-4\psi(r)} \cdot \max \left\{ \frac{|\psi'(r)|}{r}, \psi'(r)^2, |\psi''(r)| \right\}.$$

J.2.2. USING A SMOOTH TRANSITION FUNCTION

In this subsection, we construct an explicit ψ from a smooth transition function. To begin with, let us consider the *standard smooth transition function* $\tau : \mathbb{R} \rightarrow \mathbb{R}$ given by

$$\tau(x) := \begin{cases} 0, & \text{if } x < 0, \\ \left(1 + \exp\left(\frac{1}{x} - \frac{1}{1-x}\right) \right)^{-1}, & \text{if } 0 \leq x < 1, \\ 1, & \text{if } x \geq 1. \end{cases}$$

The following facts follow from single-variable calculus.

Lemma J.3 *The standard smooth transition function τ satisfies the following properties:*

- (i) $\tau : \mathbb{R} \rightarrow \mathbb{R}$ is smooth everywhere on $\mathbb{R}$.
- (ii) τ is strictly increasing on $[0, 1]$.
- (iii) $\tau(1/2) = 1/2$.
- (iv) $|\tau'(x)| \leq 2$, for every $x \in \mathbb{R}$.
- (v) $|\tau''(x)| \leq 10$, for every $x \in \mathbb{R}$.

By linear scaling (dilation), we can define scaled versions of transition function. For any real numbers a, b, h with $a < b$ and $h > 0$, we define $\tau_{a,b,h} : \mathbb{R} \rightarrow \mathbb{R}$ given by

$$\tau_{a,b,h}(x) := \begin{cases} 0, & \text{if } x < a, \\ h \cdot \tau\left(\frac{x-a}{b-a}\right), & \text{if } a \leq x < b, \\ h, & \text{if } x \geq b. \end{cases}$$

We immediately have a scaled version of Lemma J.3 above.

Lemma J.4 *The standard smooth transition function τ satisfies the following properties:*

- (i) $\tau_{a,b;h}$ is smooth everywhere on $\mathbb{R}$.
- (ii) $\tau_{a,b;h}$ is strictly increasing on $[a, b]$.
- (iii) $\tau((a+b)/2) = h/2$.
- (iv) $|\tau'_{a,b;h}(x)| \leq 2h(b-a)^{-1}$, for every $x \in \mathbb{R}$.
- (v) $|\tau''_{a,b;h}(x)| \leq 10h(b-a)^{-2}$, for every $x \in \mathbb{R}$.

Now we construct the function $\psi : [0, 0.03) \rightarrow \mathbb{R}$ explicitly:

$$\psi(x) := \begin{cases} 0, & \text{if } 0 \leq x < \frac{r_{\text{bump}}}{2} \text{ or } x \geq r_{\text{bump}}, \\ \tau_{\frac{1}{2}r_{\text{bump}}, \frac{2}{3}r_{\text{bump}}; \alpha r_{\text{bump}}^2}(x), & \text{if } \frac{r_{\text{bump}}}{2} \leq x < \frac{2}{3}r_{\text{bump}}, \\ \alpha r_{\text{bump}}^2, & \text{if } \frac{2}{3}r_{\text{bump}} \leq x < \frac{5}{6}r_{\text{bump}}, \\ 1 - \tau_{\frac{2}{3}r_{\text{bump}}, \frac{5}{6}r_{\text{bump}}; \alpha r_{\text{bump}}^2}(x), & \text{if } \frac{5}{6}r_{\text{bump}} \leq x < r_{\text{bump}}, \end{cases}$$

where we may take $\alpha \in \mathbb{R}$ to be any real number which satisfies

$$0 < \alpha < 2^{-12}\kappa.$$

It is immediate from our use of smooth transition functions that $\psi : [0, 0.03) \rightarrow \mathbb{R}$ is smooth. Furthermore, since ψ is smooth and is identically zero on an open neighborhood of 0, it follows from the chain rule that $\varphi(p) := \psi(\|p\|)$ is smooth everywhere in $B(\mathbf{0}, 0.03)$.

Proposition J.5 *The manifold (M_2, g_2) , where the metric g_2 is obtained by the conformal change as described above, has the sectional curvature bound*

$$-\kappa < K < \kappa,$$

everywhere on the manifold.

Proof This is a consequence of Proposition J.2 and Lemma J.4. Since ψ is nonnegative, Proposition J.2 implies that

$$|K| \leq 3 \cdot \max \left\{ \frac{|\psi'(r)|}{r}, \psi'(r)^2, |\psi''(r)| \right\},$$

whence it suffices to show

$$\max \left\{ \frac{|\psi'(r)|}{r}, \psi'(r)^2, |\psi''(r)| \right\} < \frac{\kappa}{3}.$$

Since ψ' vanishes on

$$\left[0, \frac{1}{2}r_{\text{bump}}\right) \cup \left(\frac{2}{3}r_{\text{bump}}, \frac{5}{6}r_{\text{bump}}\right) \cup \left(r_{\text{bump}}, 0.03\right),$$

we only need to consider the case

$$r \in \left[\frac{1}{2}r_{\text{bump}}, \frac{2}{3}r_{\text{bump}} \right] \cup \left[\frac{5}{6}r_{\text{bump}}, r_{\text{bump}} \right].$$

Now we use Lemma J.4. First,

$$\frac{|\psi'(r)|}{r} \leq 2\alpha r_{\text{bump}}^2 \left(\frac{1}{6}r_{\text{bump}} \right)^{-1} \left(\frac{1}{2}r_{\text{bump}} \right)^{-1} = 24\alpha < \frac{\kappa}{3}.$$

Second,

$$\psi'(r)^2 \leq (2\alpha r_{\text{bump}}^2)^2 \left(\frac{1}{6}r_{\text{bump}} \right)^{-2} = 144\alpha^2 r_{\text{bump}}^2 < \frac{\kappa}{3},$$

where in the last step we have used our assumptions that

$$\alpha < 2^{-12}\kappa \quad \text{and} \quad r_{\text{bump}} < \frac{\pi}{100\sqrt{\kappa}}.$$

Third,

$$|\psi''(r)| \leq 10(\alpha r_{\text{bump}}^2) \left(\frac{1}{6}r_{\text{bump}} \right)^{-2} = 360\alpha < \frac{\kappa}{3}.$$

We have finished the proof. ■

We have successfully shown that our construction provides a conformal change to the metric in a way that respects the desired sectional curvature upper bound.

J.3. Lower bound on the injectivity radius $r_{\text{inj}}(M_2)$

In the original flat torus (M_1, g_1) , it is clear that the injectivity radius is $r_{\text{inj}}(M_1) = 1/2$, which is exactly half the length of the shortest geodesic loop on M_1 . Above we have constructed (M_2, g_2) with a proven sectional curvature two-sided bounds $-\kappa < K_{M_2} < \kappa$. Potentially the injectivity radius $r_{\text{inj}}(M_2)$ might be different from that of M_1 after we added the bump. In this subsection, we provide a lower bound on $r_{\text{inj}}(M_2)$.

A crucial feature of our lower bound is that it is independent of n . Hence, the injectivity radius, even as the size of the small bump vanishes asymptotically as $n \rightarrow \infty$, remains bounded away from zero.

Our main tool for this part is the following theorem of Cheeger.

Theorem J.6 (**Cheeger (1970)**; also see (**Cheeger and Ebin, 2008, Thm. 5.8**)) *For any $d \in \mathbb{Z}_{\geq 1}$, $D > 0$, $V > 0$, and $H \in \mathbb{R}$, there exists a constant $c_{J.6} = c(d, D, V, H) > 0$, depending only on d, D, V, H , such that for every d -dimensional Riemannian manifold M with $\text{diam}(M) \leq D$, $\text{Vol}(M) \geq V$, and $K_M \geq H$, every smooth closed geodesic on M has length greater than $c_{J.6}$.*

We claim that $\text{diam}(M_2) \leq \frac{\sqrt{d}}{2} + 0.03$. To see this, note that $\text{diam}(M_1) = \frac{\sqrt{d}}{2}$. For any two points $p, q \in M_2$, consider the path γ from p to q such that $L(\gamma; M_1) = \|pq\|_{M_1}$. Note

that the difference between $L(\gamma; M_1)$ and $L(\gamma; M_2)$ can be only when γ passes through at least one of the small bumps, and this adds at most

$$N_{\text{bump}} \cdot 2r_{\text{bump}} \cdot e^{\alpha r_{\text{bump}}^2} \leq 2^{-4} e^{2^{-12} 10^{-4} \pi^2} < 0.03.$$

Thus, $L(\gamma; M_2) \leq L(\gamma; M_1) + 0.03 \leq \frac{\sqrt{d}}{2} + 0.03$.

We claim that $\text{vol}(M_2) \geq 1$. To see this, note that outside the small bump, the volume form is just the Euclidean volume form. Inside the small bump, the volume form satisfies

$$\sqrt{|\deg(g_2)|} \Big|_p = e^{d \cdot \varphi(p)} \geq 1.$$

Hence, $\text{vol}(M_2) \geq \text{vol}(M_1) = 1$.

From the previous subsection, we have shown $K_{M_2} \geq -\kappa$. Now we can show the following result.

Proposition J.7 *Let $c_{J.6} = c(d, \sqrt{d}/2 + 0.03, 1, -\kappa) > 0$ be the constant from Theorem J.6. Define*

$$c_{J.7} = c_{J.7}(d, \kappa) := \min \left\{ \frac{\pi}{\sqrt{\kappa}}, \frac{1}{2} c_{J.6} \right\} > 0.$$

Then $r_{\text{inj}}(M_2) \geq c_{J.7}$. Note that $c_{J.7}$ depends only on d and κ .

Proof This follows immediately from combining our discussions above with Klingenberg's lemma (see e.g. (Petersen, 2016, Thm. 6.4.7)). $\blacksquare$

J.4. Difference in distances

Recall that we consider two special points $X = (-2\lambda, 0, \dots, 0)$ and $Y = (2\lambda, 0, \dots, 0)$. In M_1 , the distance $|XY|_{M_1}$ is 4λ .

To ensure that $|XY|_{M_2}$ is sufficiently larger than $|XY|_{M_1}$, let us from now on take

$$\alpha := 3 \cdot 2^{-14} \kappa.$$

This subsection proves the following lower bound:

Proposition J.8 *We have*

$$|XY|_{M_2} \geq 4\lambda + 2^{-15} \lambda \kappa \cdot r_{\text{bump}}^2.$$

Proof Take an arbitrary curve γ from X to Y . We consider two cases.

Case 1. Suppose that there exists an index $i \in [N_{\text{bump}}]$ such that γ does not visit $B(Z_i, r_{\text{bump}}/2)$, the “flat” part inside of the bump centered at Z_i . In this case, note that

$$L(\gamma; M_2) \geq L(\gamma; M_1),$$

and elementary geometry gives

$$L(\gamma; M_2) \geq \sqrt{d_1^2 - \frac{r_{\text{bump}}^2}{4}} + \sqrt{d_2^2 - \frac{r_{\text{bump}}^2}{4}} + \frac{r_{\text{bump}}^2}{4d_1} + \frac{r_{\text{bump}}^2}{4d_2},$$

where $d_1 := |X Z_i|$ and $d_2 := |Z_i Y|$.

Since $d_1, d_2 \in [\lambda, 3\lambda]$, $d_1 + d_2 = 4\lambda$, and $r_{\text{bump}}/\lambda \leq 0.01$ by assumption, we use the inequality $\sqrt{1-x^2} \geq 1 - \frac{3}{4}x$ for $x \leq 0.01$ to obtain

$$L(\gamma; M_2) \geq \left(d_1 - \frac{3}{16} \frac{r_{\text{bump}}^2}{d_1}\right) + \left(d_2 - \frac{3}{16} \frac{r_{\text{bump}}^2}{d_2}\right) + \frac{r_{\text{bump}}^2}{4d_1} + \frac{r_{\text{bump}}^2}{4d_2}.$$

Hence,

$$L(\gamma; M_2) \geq 4\lambda + \frac{1}{16} \left(\frac{1}{d_1} + \frac{1}{d_2}\right) r_{\text{bump}}^2.$$

By Cauchy–Schwarz, note that

$$(d_1 + d_2) \left(\frac{1}{d_1} + \frac{1}{d_2}\right) \geq 4,$$

and thus

$$\frac{1}{d_1} + \frac{1}{d_2} \geq \frac{1}{\lambda}.$$

This shows that

$$L(\gamma; M_2) \geq 4\lambda + \frac{r_{\text{bump}}^2}{16\lambda} \geq 4\lambda + 2^{-15} \lambda \kappa r_{\text{bump}}^2,$$

where the last inequality follows from our parameter assumption that $\lambda < \frac{\pi}{\sqrt{\kappa}}$.

Case 2. Suppose that γ visits $B(Z_i, r_{\text{bump}}/2)$, for every $i \in [N_{\text{bump}}]$. Then from our construction, γ must spend at least $2 \cdot (r_{\text{bump}}/6) = r_{\text{bump}}/3$ g_1 -distance over where ψ is αr_{bump}^2 , for *each* of the N_{bump} bumps. Hence,

$$L(\gamma; M_2) \geq L(\gamma; M_1) + N_{\text{bump}} \cdot \frac{r_{\text{bump}}}{3} \cdot \left(e^{\alpha r_{\text{bump}}^2} - 1\right) \geq 4\lambda + 2^{-15} \lambda \kappa r_{\text{bump}}^2.$$

This finishes the proof of the proposition. ■

Using a similar idea, we can obtain an *upper bound* of the difference between $|pq|_{M_1}$ and $|pq|_{M_2}$ for arbitrary points p, q on the torus.

Proposition J.9 *For any two points $p, q \in \mathbb{R}^d/\mathbb{Z}^d$, we have*

$$0 \leq |pq|_{M_2} - |pq|_{M_1} < 2^{-11} \lambda \kappa \cdot r_{\text{bump}}^2.$$

Proof Take a minimizing g_1 -geodesic γ from p to q , so that $|pq|_{M_1} = L(\gamma; M_1)$. Note that the g_1 -length of $\gamma \cap B(Z_i, r_{\text{bump}})$ is at most $2r_{\text{bump}}$, for each $i \in [N_{\text{bump}}]$. Hence,

$$L(\gamma; M_2) - L(\gamma; M_1) \leq N_{\text{bump}} \cdot 2r_{\text{bump}} \left(e^{\alpha r_{\text{bump}}^2} - 1\right) \leq \frac{5}{2} \alpha \lambda r_{\text{bump}}^2.$$

Now because $\alpha = 3 \cdot 2^{-14} \kappa$, we have

$$L(\gamma; M_2) - L(\gamma; M_1) < 2^{-11} \lambda \kappa \cdot r_{\text{bump}}^2.$$

Since $L(\gamma; M_2) \geq |pq|_{M_2}$, we have finished the proof. ■

J.5. Geodesic cones

For each point $p \in \mathbb{T}^d$ and for each $i \in [N_{\text{bump}}] = \{1, 2, \dots, N_{\text{bump}}\}$, we define the “geodesic cone” $\mathcal{GC}_i(p) \subseteq \mathbb{T}^d$ to be the set of all points $q \in \mathbb{T}^d$ for which there exists a minimizing g_1 -geodesic γ connecting p and q such that

$$\gamma \cap B(Z_i, r_{\text{bump}}) \neq \emptyset.$$

Note that despite its name, the “geodesic cone” is in general not a cone, since it is missing points “between” p and the bump.

Let us prove a useful result on the volume of cones in $\mathbb{R}^d$, before working on the flat torus.

Lemma J.10 *Let $d \geq 2$, let B denote the ball $B(\mathbf{0}, r_{\text{bump}}) \subseteq \mathbb{R}^d$, and let p denote a point in $\mathbb{R}^d$ such that the distance between p and $\mathbf{0}$ is $R > r_{\text{bump}}$. Consider the following “truncated cone”*

$$\mathcal{C} := \left\{ x \in \mathbb{R}^d : \exists \lambda \in [0, \sqrt{d}], \exists q \in B, \overrightarrow{px} = \lambda \cdot \frac{\overrightarrow{pq}}{\|\overrightarrow{pq}\|} \right\}.$$

That is, $\mathcal{C}$ is the set of all points in $\mathbb{R}^d$ one can reach by starting at p and going straight in the direction of some point in the ball B for some distance at most $\sqrt{d}$.

Then

$$\text{vol}(\mathcal{C}) \leq C_{J.10} \cdot \left(\frac{r_{\text{bump}}}{R} \right)^{d-1},$$

where $C_{J.10} = C_{J.10}(d) > 0$ is a constant depending only on d .

Proof We distinguish two regimes. First, if $R \leq 2r_{\text{bump}}$, then we simply use the trivial bound: the volume of the cone is bounded above by the volume of the d -dimensional ball of radius $\sqrt{d}$, which is a constant depending only on d . Since in this regime $r_{\text{bump}}/R \geq 1/2$, we can take the constant to be 2^{d-1} times the volume of the ball.

Second, let us consider the regime where $R > 2r_{\text{bump}}$. It is not hard to see that

$$\text{vol}(\mathcal{C}) \ll_d \left(\frac{r_{\text{bump}}}{R \sqrt{1 - \left(\frac{r_{\text{bump}}}{R} \right)^2}} \right)^{d-1}.$$

Since $r_{\text{bump}}/R < 1/2$, we have $\sqrt{1 - \left(\frac{r_{\text{bump}}}{R} \right)^2} > \frac{\sqrt{3}}{2}$, and thus

$$\text{vol}(\mathcal{C}) \ll_d \left(\frac{r_{\text{bump}}}{R} \right)^{d-1},$$

as desired. ■

Remark J.11 *The lemma above gives only the upper bound on the volume of the cone, which is sufficient for our purposes. It is possible to obtain an exact formula for the volume, but it is rather complicated and involves the incomplete Beta function. See e.g. the answer by [incomunicado](#) (2022).*

Now we work on the flat torus.

Lemma J.12 *Let $p \in \mathbb{T}^d$ and $i \in [N_{\text{bump}}]$. Let $R := |p Z_i|_{g_1} \geq 0$. Then*

$$\text{vol}(\mathcal{GC}_i(p)) \leq C_{J.12} \cdot \min\left\{\frac{r_{\text{bump}}}{R}, 1\right\}^{d-1},$$

where $C_{J.12} = C_{J.12}(d) > 0$ is a constant depending only on d .

Proof If $R \leq r_{\text{bump}}$, which means that p is a point in the closure of the bump, then the volume of $\mathcal{GC}_i(p)$ is upper bound by the total volume of the torus, which is 1.

Now suppose $R > r_{\text{bump}}$. For convenience of presentation, let us place, without loss of generality, the point p at $(1/2, 1/2, \dots, 1/2) \in \mathbb{T}^d$, and let us also represent the points in $\mathbb{T}^d$ by $[0, 1]^d$ (with the usual understanding that the sides of the cubes are glued in the correct way).

If the center Z_i of the bump lies within the cube $(r_{\text{bump}}, 1 - r_{\text{bump}})^d$, then the volume of $\mathcal{GC}_i(p)$ is bounded above by the volume of the cone in $\mathbb{R}^d$ as in the previous lemma. Hence, the previous lemma gives us a constant depending only on d .

Finally, if Z_i lies outside of the cube $(r_{\text{bump}}, 1 - r_{\text{bump}})^d$, it could potentially happen that the bump gets sliced so it appears on the opposite sides of $[0, 1]^d$. From p , the “geodesic cone” in this case would like like multiple cones in the opposite direction at p . Note, however, that the number of sliced pieces is at most 2^d . And thus, we can simply take our constant to be 2^d times the constant from the previous lemma, in this regime.

Taking the maximum of the constants from the three regimes gives us the desired result. ■

J.6. Coupling

We define the following coupling: take $W_1, \dots, W_n$ i.i.d. $\text{Unif}(0, 1)$. For each i , if $W_i \leq 1 - 2m$, then take $X_i \sim \text{Unif}(\mathbb{T}^d)$. If $1 - 2m < W_i \leq 1 - m$, then $X_i := X$. If $W_i > 1 - m$, then $X_i := Y$.

Note that the n latent points $X_1, \dots, X_n$ are sampled on M_1 and on M_2 simultaneously according to μ . This gives the coupling between the two random geometric graphs G_1 (on M_1) and G_2 (on M_2).

For points $p, q \in \mathbb{T}^d$, we define $\mathcal{T}(p, q)$ to be the event where there exists a minimizing g_1 -geodesic connecting p and q that intersects with $\bigcup_{k=1}^{N_{\text{bump}}} B(Z_k, r_{\text{bump}})$. Note that $\mathcal{T}(p, q) = \mathcal{T}(q, p)$, and that $\mathcal{T}(p, q)$ is the event

$$\left\{ p \in \bigcup_{k=1}^{N_{\text{bump}}} \mathcal{GC}_k(q) \right\} = \bigcup_{k=1}^{N_{\text{bump}}} \{p \in \mathcal{GC}_k(q)\}.$$

Thus, by the union bound, for i.i.d. points $p, q \sim \text{Unif}(\mathbb{T}^d)$, and by invoking Lemma J.12, we have

$$\mathbb{P}(\mathcal{T}(p, q)) \leq \sum_{k=1}^{N_{\text{bump}}} \mathbb{P}\{p \in \mathcal{GC}_k(q)\}.$$

Now consider a point $Y \sim \text{uniform}(\mathbb{T}^d)$ according to the standard Lebesgue measure induced on the flat torus. Let $\mathfrak{R}$ denote the g_1 -geodesic distance from Y to $\mathbf{0}$. It is not hard to see that $\mathfrak{R}$ is absolutely continuous, so let us write $f_{\mathfrak{R}}$ for the unique continuous density of $\mathfrak{R}$. Then the following estimate on $f_{\mathfrak{R}}$ of $\mathfrak{R}$ follows from the volume formula for spheres:

Lemma J.13 *For $0 \leq R \leq \frac{\sqrt{d}}{2}$, we have*

$$f_{\mathfrak{R}}(R) \leq C_{J.13} \cdot R^{d-1},$$

where $C_{J.13} = C_{J.13}(d) > 0$ is a constant depending only on d .

Therefore, we obtain the following lemma.

Lemma J.14 *For i.i.d. points $p, q \in \text{Unif}(\mathbb{T}^d)$ and for $k \in [N_{\text{bump}}]$, we have*

$$\mathbb{P}\{p \in \mathcal{GC}_k(q)\} \leq C_{J.14} \cdot r_{\text{bump}}^{d-1},$$

where $C_{J.14} = C_{J.14}(d) > 0$ is a constant depending only on d .

Proof By combining Lemmas J.12 and J.13, we obtain

$$\begin{aligned} \mathbb{P}\{p \in \mathcal{GC}_k(q)\} &\leq \int_0^{\sqrt{d}/2} \mathbb{P}\{p \in \mathcal{GC}_k(q) \mid |Z_k q|_{g_1} = R\} \cdot f_{\mathfrak{R}}(R) \, dR \\ &\leq \int_0^{\sqrt{d}/2} C_{J.12} \min\left\{\frac{r_{\text{bump}}}{R}, 1\right\}^{d-1} \cdot C_{J.13} R^{d-1} \, dR \\ &\leq_d r_{\text{bump}}^{d-1}. \end{aligned}$$

■

Hence, by combining with the union bound above, we have

$$\mathbb{P}(\mathcal{T}(p, q)) \ll_{d, \kappa} r_{\text{bump}}^{d-2}.$$

Recall that by Proposition J.9, for any two points $x, y \in \mathbb{T}^d$, we know

$$0 < |x y|_{g_2} - |x y|_{g_1} \leq_{d, \kappa} r_{\text{bump}}^2.$$

Therefore, by conditioning on whether W_i and W_j are in $[0, 1 - 2m]$, $(1 - 2m, 1 - m]$, or $(1 - m, 1]$, for any $i, j \in [n]$, we have that the probability that there is an edge between i and j in M_1 but not in M_2 is bounded by

$$\leq_{d, \kappa} (1 - 2m)^2 \cdot r_{\text{bump}}^2 \cdot r_{\text{bump}}^{d-2} + 4m \cdot r_{\text{bump}}^2 \cdot r_{\text{bump}}^{d-2} + 4m^2 \cdot r_{\text{bump}}^2 \leq_{d, \kappa} \frac{1}{n^2 (\log n)^{d/2}}.$$

Thus, by the union bound,

$$\mathbb{P}\{G_1 \neq G_2\} = o(1),$$

as $n \rightarrow \infty$.

J.7. Final steps

We have shown that $G_1 = G_2$ with high probability. It is not hard to see that our construction satisfies the regularity assumptions on p , μ , and M_i . It remains to show that both X and Y appear as latent points with high probability.

This last step is simple. We have

$$\mathbb{P}\{\forall i \in [n], W_i \leq 1 - 2m\} = (1 - 2m)^n \leq e^{-2mn} \rightarrow 0,$$

since $m = \frac{\log n}{n}$.

Finally, from Proposition J.8, the distance discrepancy is

$$|XY|_{g_2} - |XY|_{g_1} \geq_{d,\kappa} r_{\text{bump}}^2 \geq_{d,\kappa} n^{-4/d} \cdot (\log n)^{-1}.$$

This finishes the proof of the lower bound claim.