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On the Optimality of Gluing over Scales

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Abstract We show that for every $\alpha > 0$, there exist n-point metric spaces (X, d) where every "scale" admits a Euclidean embedding with distortion at most α, but the whole space requires distortion at least $\Omega(\sqrt{\alpha \log n})$. This shows that the scale-gluing lemma (Lee in SODA'05: Proceedings of the 18th Annual ACM-SIAM Symposium on Discrete Algorithms, pp. 92–101, Society for Industrial and Applied Mathematics, Philadelphia, 2005) is tight and disproves a conjecture stated there. This matching upper bound was known to be tight at both endpoints, i.e., when $\alpha = \Theta(1)$ and $\alpha = \Theta(\log n)$, but nowhere in between.

More specifically, we exhibit n-point spaces with doubling constant λ requiring Euclidean distortion $\Omega(\sqrt{\log \lambda \log n})$, which also shows that the technique of "measured descent" (Krauthgamer et al. in Geom. Funct. Anal. 15(4):839–858, 2005) is optimal. We extend this to L_p spaces with $p > 1$, where one requires distortion at least $\Omega((\log n)^{1/q} (\log \lambda)^{1-1/q})$ when $q = \max\{p, 2\}$, a result which is tight for every $p > 1$.

Keywords Finite metric spaces · Euclidean distortion · Metric geometry

1 Introduction

Suppose that we are given a collection of mappings from some finite metric space (X, d) into a Euclidean space, each of which reflects the geometry at some "scale" of X. Is there a nontrivial way of gluing these mappings together to form a global mapping which reflects the entire geometry of X? The answers to such questions have played a fundamental role in the best-known approximation algorithms for Sparsest

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Cut [1, 4, 7, 10] and Graph Bandwidth [7, 11, 17], and have found applications in approximate multicommodity max-flow/min-cut theorems in graphs [7, 17]. In the present paper, we show that the approaches of [7] and [10] are optimal, disproving a conjecture stated in [10].

Let (X, d) be an n-point metric space, and suppose that for every $k \in \mathbb{Z}$, we are given a nonexpansive mapping $\phi_k : X \to L_2$ which satisfies the following. For every $x, y \in X$ with $d(x, y) \geq 2^k$, we have

$$\left\| \phi_k(x) - \phi_k(y) \right\| \geq \frac{2^k}{\alpha}.$$

The Gluing Lemma of [10] (generalizing the approach of [7]) shows that the existence of such a collection $\{\phi_k\}$ yields a Euclidean embedding of (X, d) with distortion $O(\sqrt{\alpha \log n})$. (See Sect. 1.1 for the relevant definitions on embeddings and distortion.) This is known to be tight when $\alpha = \Theta(1)$ [16] and also when $\alpha = \Theta(\log n)$ [2, 13], but nowhere in between. In fact, in [10], the second-named author conjectured that one could achieve $O(\alpha + \sqrt{\log n})$ (this is indeed stronger, since one can always construct $\{\phi_k\}$ with $\alpha = O(\log n)$).

In the present paper, we give a family of examples which shows that the $\sqrt{\alpha \log n}$ bound is tight for any dependence $\alpha(n) = O(\log n)$. In fact, we show more. Let $\lambda(X)$ denote the *doubling constant* of X, i.e., the smallest number λ such that every open ball in X can be covered by λ balls of half the radius. In [7], using the method of "measure descent," the authors show that (X, d) admits a Euclidean embedding with distortion $O(\sqrt{\log \lambda(X) \log n})$. (This is a special case of the Gluing Lemma since one can always find $\{\phi_k\}$ with $\alpha = O(\log \lambda(X))$ [5].) Again, this bound was known to be tight for $\lambda(X) = \Theta(1)$ [5, 8, 9] and $\lambda(X) = n^{\Theta(1)}$ [2, 13], but nowhere in between. We provide the matching lower bound for any dependence of $\lambda(X)$ on n. We also generalize our method to give tight lower bounds on L_p distortion for every fixed $p > 1$.

Construction and Analysis In some sense, our lower bound examples are an interpolation between the multiscale method of [16] and [8], and the expander Poincaré inequalities of [2, 13, 14]. We start with a vertex-transitive expander graph G on m nodes. If D is the diameter of G, then we create $D + 1$ copies $G^1, G^2, \ldots, G^{D+1}$ of G where $u \in G^i$ is connected to $v \in G^{i+1}$ if (u, v) is an edge in G or if $u = v$. We then connect a vertex s to every node in G^1 and a vertex t to every node in G^{D+1} by edges of length D. This yields the graph $\vec{G}$ described in Sect. 2.2.

In Sect. 3, we show that whenever there is a noncontracting embedding f of $\vec{G}$ into L_2, the following holds. If $\gamma = \frac{\|f(s)-f(t)\|}{d_{\vec{G}}(s,t)}$, then some edge of $\vec{G}$ gets stretched by at least $\sqrt{\gamma^2 + \Omega(\log m)^2}$, i.e., there is a "stretch increase." This is proved by combining the uniform convexity of L_2 (i.e., the Pythagorean theorem) with the well-known contraction property of expander graphs mapped into Hilbert space. To convert the "average" nature of this contraction to information about a specific edge, we symmetrize the embedding over all automorphisms of G (which was chosen to be vertex-transitive).

To exploit this stretch increase recursively, we construct a graph $\vec{G}^{\oslash k}$ inductively as follows: $\vec{G}^{\oslash k}$ is formed by replacing every edge of $\vec{G}^{\oslash k-1}$ by a copy of $\vec{G}$ (see

Sect. 2.1 for the formal definitions). Now a simple induction shows that in a noncontracting embedding of $\vec{G}^{\oslash k}$, there must be an edge stretched by at least $\Omega(\sqrt{k}\log m)$. In Sect. 3.1, a similar argument is made for L_p distortion, for $p > 1$, but here we have to argue about "quadrilaterals" instead of "triangles" (in order to apply the uniform convexity inequality in L_p), and it requires slightly more effort to find a good quadrilateral.

Finally, we observe that if $\widetilde{G}$ is the graph formed by adding two tails of length $3D$ hanging off s and t in $\vec{G}$, then (following the analysis of [8, 9]), one has $\log\lambda(\widetilde{G}^{\oslash k}) \lesssim \log m$. The same lower bound analysis also works for $\widetilde{G}^{\oslash k}$, so since $n = |V(\widetilde{G}^{\oslash k})| = 2^{\Theta(k\log m)}$, the lower bound is

$$\sqrt{k}\log m \approx \sqrt{\log m \log n} \gtrsim \sqrt{\log\lambda\big(\widetilde{G}^{\oslash k}\big)\log n},$$

completing the proof.

1.1 Preliminaries

For a graph G, we will use $V(G), E(G)$ to denote the sets of vertices and edges of G, respectively. Sometimes we will equip G with a nonnegative length function $\mathsf{len} : E(G) \to \mathbb{R}_+$, and we let d_{len} denote the shortest-path (semi-)metric on G. We refer to the pair (G, len) as a *metric graph,* and often len will be implicit, in which case we use d_G to denote the path metric. We use $\mathsf{Aut}(G)$ to denote the group of automorphisms of G.

Given two expressions E and E' (possibly depending on a number of parameters), we write $E = O(E')$ to mean that $E \le CE'$ for some constant $C > 0$ which is independent of the parameters. Similarly, $E = \Omega(E')$ implies that $E \ge CE'$ for some $C > 0$. We also write $E \lesssim E'$ as a synonym for $E = O(E')$. Finally, we write $E \approx E'$ to denote the conjunction of $E \lesssim E'$ and $E \gtrsim E'$.

Embeddings and Distortion If $(X, d_X), (Y, d_Y)$ are metric spaces and $f : X \to Y$, then we write

$$\|f\|_{\mathrm{Lip}} = \sup_{x\neq y\in X} \frac{d_Y(f(x), f(y))}{d_X(x, y)}.$$

If f is injective, then the *distortion of f* is defined by $\mathrm{dist}(f) = \|f\|_{\mathrm{Lip}} \cdot \|f^{-1}\|_{\mathrm{Lip}}$. A map with distortion D will sometimes be referred to as *D-bi-Lipschitz.* If $d_Y(f(x), f(y)) \le d_X(x, y)$ for every $x, y \in X$, we say that f is *nonexpansive.* If $d_Y(f(x), f(y)) \ge d_X(x, y)$ for every $x, y \in X$, we say that f is *noncontracting.* For a metric space X, we use $c_p(X)$ to denote the least distortion required to embed X into some L_p space.

Finally, for $x \in X$ and $r \in \mathbb{R}_+$, we define the open ball $B(x, r) = \{y \in X : d(x, y) < r\}$. Recall that the *doubling constant* of a metric space (X, d) is the infimum over all values λ such that every ball in X can be covered by λ balls of half the radius. We use $\lambda(X, d)$ to denote this value.

We now state the main theorem of the paper.

Theorem 1.1 *For any positive nondecreasing function $\lambda(n)$, there exists a family of n-vertex metric graphs $\widetilde{G}^{\oslash k}$ such that $\lambda(\widetilde{G}^{\oslash k}) \lesssim \lambda(n)$, and for every fixed $p > 1$,*

$$c_p\big(\widetilde{G}^{\oslash k}\big) \gtrsim (\log n)^{1/q}\big(\log \lambda(n)\big)^{1-1/q},$$

where $q = \max\{p, 2\}$.

2 Metric Construction

2.1 $\oslash$-products

An s–t graph G is a graph which has two distinguished vertices $s, t \in V(G)$. For an s–t graph, we use $s(G)$ and $t(G)$ to denote the vertices labeled s and t, respectively. We define the length of an s–t graph G as $\mathsf{len}(G) = d_{\mathsf{len}}(s, t)$.

Definition 2.1 (Composition of s–t graphs) Given two s–t graphs H and G, define $H \oslash G$ to be the s–t graph obtained by replacing each edge $(u, v) \in E(H)$ by a copy of G (see Fig. 1). Formally,

- $V(H \oslash G) = V(H) \cup (E(H) \times (V(G) \setminus \{s(G), t(G)\}))$.
- For every edge $e = (u, v) \in E(H)$, there are $|E(G)|$ edges,

$$\big\{\big((e, v_1), (e, v_2)\big) \,\big|\, (v_1, v_2) \in E(G) \text{ and } v_1, v_2 \notin \big\{s(G), t(G)\big\}\big\}$$
$$\cup \big\{\big(u, (e, w)\big) \,\big|\, \big(s(G), w\big) \in E(G)\big\} \cup \big\{\big((e, w), v\big) \,\big|\, \big(w, t(G)\big) \in E(G)\big\}.$$

- $s(H \oslash G) = s(H)$ and $t(H \oslash G) = t(H)$.

If H and G are equipped with length functions len_H, len_G, respectively, we define $\mathsf{len} = \mathsf{len}_{H \oslash G}$ as follows. Using the preceding notation, for every edge $e = (u, v) \in E(H)$,

$$\mathsf{len}\big((e, v_1), (e, v_2)\big) = \frac{\mathsf{len}_H(e)}{d_{\mathsf{len}_G}(s(G), t(G))}\mathsf{len}_G(v_1, v_2),$$
$$\mathsf{len}\big(u, (e, w)\big) = \frac{\mathsf{len}_H(e)}{d_{\mathsf{len}_G}(s(G), t(G))}\mathsf{len}_G\big(s(G), w\big),$$
$$\mathsf{len}\big((e, w), v\big) = \frac{\mathsf{len}_H(e)}{d_{\mathsf{len}_G}(s(G), t(G))}\mathsf{len}_G\big(w, t(G)\big).$$

This choice implies that $H \oslash G$ contains an isometric copy of $(V(H), d_{\mathsf{len}_H})$.

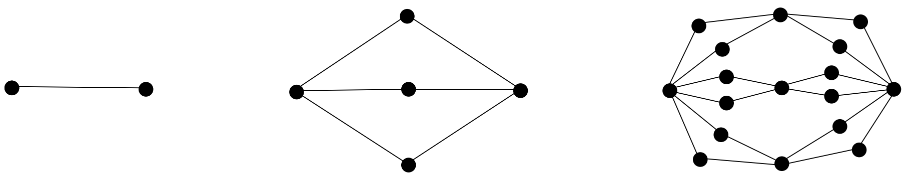

Fig. 1 A single edge H, $H \oslash K_{2,3}$, and $H \oslash K_{2,3} \oslash K_{2,2}$

Observe that there is some ambiguity in the definition above, as there are two ways to substitute an edge of H with a copy of G; thus we assume that there exists some arbitrary orientation of the edges of H. However, for our purposes, the graph G will be symmetric, and thus the orientations are irrelevant.

Definition 2.2 (Recursive composition) For an s–t graph G and a number $k \in \mathbb{N}$, we define $G^{\oslash k}$ inductively by letting $G^{\oslash 0}$ be a single edge of unit length and setting $G^{\oslash k} = G^{\oslash k-1} \oslash G$.

The following result is straightforward.

Lemma 2.3 (Associativity of $\oslash$) *For any three graphs A, B, C, we have $(A \oslash B) \oslash C = A \oslash (B \oslash C)$, both graph-theoretically and as metric spaces.*

Definition 2.4 For two graphs G, H, a subset of vertices $X \subseteq V(H)$ is said to be a *copy* of G if there exists a bijection $f : V(G) \to X$ with distortion 1, i.e., $d_H(f(u), f(v)) = C \cdot d_G(u, v)$ for some constant $C > 0$.

Now we make the following two simple observations about copies of H and G in $H \oslash G$.

Observation 2.5 The graph $H \oslash G$ contains $|E(H)|$ distinguished copies of the graph G, one copy corresponding to each edge in H.

Observation 2.6 The subset of vertices $V(H) \subseteq V(H \oslash G)$ forms an isometric *copy* of H.

2.2 A Stretched $\vec{G}$

Let $G = (V, E)$ be an unweighted graph, and put $D = \mathrm{diam}(G)$. We define a metric s–t graph $\vec{G}$ which has $D + 1$ layers isomorphic to G, with edges between the layers, and a pair of endpoints s, t. Formally,

$$
\begin{aligned}
V(\vec{G}) &= \{s, t\} \cup \left\{v^{(i)} : v \in V, i \in [D+1]\right\},\\
E(\vec{G}) &= \left\{\left(s, v^{(1)}\right), \left(v^{(D+1)}, t\right) : v \in V\right\}\\
&\qquad \cup \left\{\left(u^{(i)}, v^{(i+1)}\right), \left(u^{(j)}, v^{(j)}\right) : (u, v) \in E, i \in [D], j \in [D+1]\right\}\\
&\qquad \cup \left\{\left(v^{(i)}, v^{(i+1)}\right) : v \in V, i \in [D]\right\}.
\end{aligned}
$$

We put $\mathsf{len}(s, v^{(1)}) = \mathsf{len}(v^{(D+1)}, t) = D$ for $v \in V$, $\mathsf{len}(u^{(i)}, v^{(i+1)}) = \mathsf{len}(u^{(j)}, v^{(j)}) = 1$ for $(u, v) \in E$, $i \in [D]$, $j \in [D + 1]$, and $\mathsf{len}(v^{(i)}, v^{(i+1)}) = 1$ for $v \in V, i \in [D]$. We refer to edges of the form $(u^{(i)}, v^{(i)})$ as *vertical edges.* All other edges are called *horizontal edges.* In particular, there are $D + 1$ copies $G^{(1)}, \dots, G^{(D+1)}$ of G in $\vec{G}$ which are isometric to G itself, and their edges are all vertical.

A Doubling Version, Following Laakso Let $\vec{G}$ be a stretched graph as in Sect. 2.2, with $D = \mathrm{diam}(G)$, and let $s' = s(\vec{G})$, $t' = t(\vec{G})$. Consider a new metric s–t graph $\widetilde{G}$, which has two new vertices s, t and two new edges $(s, s'), (t', t)$ with $\mathsf{len}(s, s') = \mathsf{len}(t', t) = 3D$.

Claim 2.7 *For any graph G with $|V(G)| = m$ and any $k \in \mathbb{N}$, we have* $\log \lambda(\widetilde{G}^{\oslash k}) \lesssim \log m$.

The proof of the claim is similar to [8, 9] and follows from the following three results.

We define $\mathrm{tri}(G) = \max_{v \in V(G)}(d_{\mathsf{len}}(s, v) + d_{\mathsf{len}}(v, t))$. For any graph G, we have $\mathsf{len}(\widetilde{G}) = d(s, t) = 9D$, and it is not hard to verify that $\mathrm{tri}(\widetilde{G}^{\oslash k}) \le \mathsf{len}(\widetilde{G}^{\oslash k})(1 + \frac{1}{9D-1})$. For convenience, let G_0 be the top-level copy of $\widetilde{G}$ in $\widetilde{G}^{\oslash k}$, and H be the graph $\widetilde{G}^{\oslash k-1}$. Then for any $e \in E(G_0)$, we refer to the copy of H along edge e as H_e.

Observation 2.8 If $r > \frac{\mathrm{tri}(\widetilde{G}^{\oslash k})}{3}$, then the ball $B(x, r)$ in $\widetilde{G}^{\oslash k}$ may be covered by at most $|V(\widetilde{G})|$ balls of radius $r/2$.

Proof For any $e \in E(G_0)$, we have $r > \frac{\mathsf{len}(e)}{\mathsf{len}(H)}\mathrm{tri}(H)$, so every point in H_e is less than $r/2$ from an endpoint of e. Thus all of $\widetilde{G}^{\oslash k}$ are covered by placing balls of radius $\frac{\mathrm{tri}(\widetilde{G}^{\oslash k})}{6}$ around each vertex of G_0. □

Lemma 2.9 *If $s \in B(x, r)$, then one can cover the ball $B(x, r)$ in $\widetilde{G}^{\oslash k}$ with at most $|E(\widetilde{G})||V(\widetilde{G})|$ balls of radius $r/2$.*

Proof First consider the case in which $r > \frac{\mathsf{len}(\widetilde{G}^{\oslash k})}{6}$. Then for any edge e in $\widetilde{G}^{\oslash k}$, we have $r > \frac{\mathsf{len}(e)}{\mathsf{len}(H)} \cdot \frac{\mathrm{tri}(H)}{3}$. Thus by Observation 2.8, we may cover H_e by $|V(\widetilde{G})|$ balls of radius $r/2$. This gives a covering of all of $\widetilde{G}^{\oslash k}$ by at most $|E(\widetilde{G})||V(\widetilde{G})|$ balls of radius $r/2$.

Otherwise, assume that $\frac{\mathsf{len}(\widetilde{G}^{\oslash k})}{6} \ge r$. Since $s \in B(x, r)$ but $2r \le \frac{\mathsf{len}(\widetilde{G}^{\oslash k})}{3}$, the ball must be completely contained inside $H_{(s,s')}$. By induction, we can find a sufficient cover of this smaller graph. □

Lemma 2.10 *We can cover any ball $B(x, r)$ in $\widetilde{G}^{\oslash k}$ with at most $2|V(\widetilde{G})||E(\widetilde{G})|^2$ balls of radius $r/2$.*

Proof We prove this lemma using induction. For $\widetilde{G}^{\oslash 0}$, the claim holds trivially. Next, if any H_e contains all of $B(x, r)$, then by induction we are done. Otherwise, for each H_e containing x, $B(x, r)$ contains an endpoint of e. Then by Lemma 2.9, we may cover H_e by at most $|E(\widetilde{G})||V(\widetilde{G})|$ balls of radius $r/2$. For all other edges $e' = (u, v)$, $x \notin H_{e'}$, so we have:

$$V(H_{e'}) \cap B(x, r) \subseteq B\big(v, \max\big(0, r - d(x, v)\big)\big) \cup B\big(u, \max\big(0, r - d(x, u)\big)\big).$$

Thus, using Lemma 2.9 on both of the above balls, we may cover $V(H_{e'}) \cap B(x,r)$ by at most $2|E(\widetilde{G})||V(\widetilde{G})|$ balls of radius $r/2$. Hence, in total, we need at most $2|V(\widetilde{G})||E(\widetilde{G})|^2$ balls of radius $r/2$ to cover all of $B(x,r)$. □

Proof of Claim 2.7 First note that $|V(\widetilde{G})| = m(D+1)+2 \lesssim m^2$. By Lemma 2.10, we have

$$\lambda(\widetilde{G}^{\oslash k}) \le 2\big|V(\widetilde{G})\big|\big|E(\widetilde{G})\big|^2 \le 2\big|V(\widetilde{G})\big|^5 \lesssim m^{10}.$$

Hence $\log \lambda(\widetilde{G}^{\oslash k}) \lesssim \log m$. □

3 Lower Bound

For any $\pi \in \mathsf{Aut}(G)$, we define a corresponding automorphism $\tilde{\pi}$ of $\tilde{G}$ by $\tilde{\pi}(s) = s$, $\tilde{\pi}(t) = t$, $\tilde{\pi}(s') = s'$, $\tilde{\pi}(t') = t'$, and $\tilde{\pi}(v^{(i)}) = \pi(v)^{(i)}$ for $v \in V$, $i \in [D+1]$.

Lemma 3.1 *Let G be a vertex transitive graph. Let $f : V(\widetilde{G}) \to L_2$ be an injective mapping and define $\bar{f} : V(\widetilde{G}) \to L_2$ by*

$$\bar{f}(x) = \frac{1}{\sqrt{|\mathsf{Aut}(G)|}}\big(f(\widetilde{\pi}x)\big)_{\pi \in \mathsf{Aut}(G)}.$$

Let β be such that for every $i \in [D+1]$, there exists a vertical edge $(u^{(i)}, v^{(i)})$ with $\|\bar{f}(u^{(i)}) - \bar{f}(v^{(i)})\| \ge \beta$. Then there exists a horizontal edge $(x,y) \in E(\widetilde{G})$ such that

$$\frac{\|\bar{f}(x) - \bar{f}(y)\|^2}{d_{\widetilde{G}}(x,y)^2} \ge \frac{\|\bar{f}(s) - \bar{f}(t)\|^2}{d_{\widetilde{G}}(s,t)^2} + \frac{\beta^2}{36}. \tag{1}$$

Proof Let $D = \operatorname{diam}(G)$. We first observe three facts about $\bar{f}$, which rely on the fact that when $\mathsf{Aut}(G)$ is transitive, for every $x \in V$, the orbits $\{\pi(x)\}_{\pi \in \mathsf{Aut}(G)}$ all have the same cardinality.

(F1) $\|\bar{f}(s) - \bar{f}(t)\| = \|f(s) - f(t)\|$.

(F2) For all $u, v \in V$,

$$\big\|\bar{f}(s) - \bar{f}\big(v^{(1)}\big)\big\| = \big\|\bar{f}(s) - \bar{f}\big(u^{(1)}\big)\big\|,$$
$$\big\|\bar{f}(t) - \bar{f}\big(v^{(D+1)}\big)\big\| = \big\|\bar{f}(t) - \bar{f}\big(u^{(D+1)}\big)\big\|.$$

(F3) For all $u, v \in V$, $i \in [D]$,

$$\big\|\bar{f}\big(v^{(i)}\big) - \bar{f}\big(v^{(i+1)}\big)\big\| = \big\|\bar{f}\big(u^{(i)}\big) - \bar{f}\big(u^{(i+1)}\big)\big\|.$$

(F4) For every pair of vertices $u, v \in V$ and $i \in [D+1]$,

$$\big\langle \bar{f}(s) - \bar{f}(t), \bar{f}\big(u^{(i)}\big) - \bar{f}\big(v^{(i)}\big)\big\rangle = 0.$$

Let $z = \frac{\bar{f}(s)-\bar{f}(t)}{\|\bar{f}(s)-\bar{f}(t)\|}$. Fix some $r \in V$ and let $\rho_0 = |\langle z, \bar{f}(s) - \bar{f}(r^{(1)})\rangle|$, $\rho_i = |\langle z, \bar{f}(r^{(i)}) - \bar{f}(r^{(i+1)})\rangle|$ for $i = 1, 2, \dots, D$ and $\rho_{D+1} = |\langle z, \bar{f}(t) - \bar{f}(r^{(D+1)})\rangle|$. Note that, by (F2) and (F3) above, the values $\{\rho_i\}$ do not depend on the representative $r \in V$. In this case, we have

$$\sum_{i=0}^{D+1} \rho_i \geq \|\bar{f}(s) - \bar{f}(t)\| = 9\gamma D, \tag{2}$$

where we put $\gamma = \frac{\|\bar{f}(s)-\bar{f}(t)\|}{d_{\widetilde{G}}(s,t)}$. Note that $\gamma > 0$ since f is injective.

Recalling that $d_{\widetilde{G}}(s,t) = 9D$ and $d_{\widetilde{G}}(s, r^{(1)}) = 4D$, observe that if $\rho_0^2 \geq (1 + \frac{\beta^2}{36\gamma^2})(4\gamma D)^2$, then

$$\max\left(\frac{\|\bar{f}(s) - \bar{f}(s')\|^2}{d_{\widetilde{G}}(s,s')^2}, \frac{\|\bar{f}(s') - \bar{f}(r^{(1)})\|^2}{d_{\widetilde{G}}(s', r^{(1)})^2}\right) \geq \gamma^2 + \frac{\beta^2}{36},$$

verifying (1). The symmetric argument holds for ρ_{D+1}, and thus we may assume that

$$\rho_0, \rho_{D+1} \leq 4\gamma D\sqrt{1 + \frac{\beta^2}{36\gamma^2}} \leq 4\gamma D\left(1 + \frac{\beta^2}{72\gamma^2}\right).$$

In this case, by (2), there must exist an index $j \in [D]$ such that

$$\rho_j \geq \left(1 - \frac{8\beta^2}{72\gamma^2}\right)\gamma = \left(1 - \frac{\beta^2}{9\gamma^2}\right)\gamma.$$

Now, consider a vertical edge $(u^{(j+1)}, v^{(j+1)})$ with $\|\bar{f}(u^{(j)}) - \bar{f}(v^{(j)})\| \geq \beta$, and let

$$u' = \bar{f}\bigl(u^{(j)}\bigr) + \bigl\langle z, \bar{f}\bigl(u^{(j)}\bigr) - \bar{f}\bigl(u^{(j+1)}\bigr)\bigr\rangle z.$$

From (F4) and the Pythagorean inequality we have

$$\begin{aligned}
&\max\bigl(\|\bar{f}\bigl(u^{(j)}\bigr) - \bar{f}\bigl(u^{(j+1)}\bigr)\|^2, \|\bar{f}\bigl(u^{(j)}\bigr) - \bar{f}\bigl(v^{(j+1)}\bigr)\|^2\bigr) \\
&\quad= \|\bar{f}\bigl(u^{(j)}\bigr) - u'\|^2 + \max\bigl(\|u' - \bar{f}\bigl(u^{(j+1)}\bigr)\|^2, \|u' - \bar{f}\bigl(v^{(j+1)}\bigr)\|^2\bigr) \\
&\quad\geq \rho_j^2 + \frac{\beta^2}{4} \\
&\quad\geq \left(1 - \frac{2\beta^2}{9\gamma^2}\right)\gamma^2 + \frac{\beta^2}{4} \\
&\quad\geq \gamma^2 + \frac{\beta^2}{36},
\end{aligned}$$

again verifying (1) for one of the two edges $(u^{(j)}, v^{(j+1)})$ or $(u^{(j)}, u^{(j+1)})$. □

The following lemma is well known and follows from the variational characterization of eigenvalues (see, e.g., [15, Chap. 15]).

Lemma 3.2 *If $G=(V,E)$ is a d-regular graph with second Laplacian eigenvalue $\mu_2(G)$, then for any mapping $f:V\to L_2$, we have*

$$\mathbb{E}_{x,y\in V}\big\|f(x)-f(y)\big\|^2 \lesssim \frac{d}{\mu_2(G)}\mathbb{E}_{(x,y)\in E}\big\|f(x)-f(y)\big\|^2. \tag{3}$$

The next lemma shows that when we use an expander graph, we get a significant increase in stretch for edges of $\widetilde{G}$.

Lemma 3.3 *Let $G=(V,E)$ be a d-regular vertex-transitive graph with $m=|V|$ and $\mu_2=\mu_2(G)$. If $f:V(\widetilde{G})\to L_2$ is any noncontractive mapping, then there exists a horizontal edge $(x,y)\in E(\widetilde{G})$ with*

$$\frac{\|f(x)-f(y)\|^2}{d_{\widetilde{G}}(x,y)^2} \geq \frac{\|f(s)-f(t)\|^2}{d_{\widetilde{G}}(s,t)^2} + \Omega\left(\frac{\mu_2}{d}(\log_d m)^2\right). \tag{4}$$

Proof We need only prove the existence of $(x,y)\in E(\widetilde{G})$ such that (4) is satisfied for $\bar{f}$ (as defined in Lemma 3.1), as this implies that it is also satisfied for f (possibly for some other edge (x,y)).

Consider any layer $G^{(i)}$ in $\widetilde{G}$ for $i\in[D+1]$. Applying (3) and using the fact that f is noncontracting, we have

$$\begin{aligned}\mathbb{E}_{(u,v)\in E}\big\|\bar{f}\big(u^{(i)}\big)-\bar{f}\big(v^{(i)}\big)\big\|^2 &= \mathbb{E}_{(u,v)\in E}\big\|f\big(u^{(i)}\big)-f\big(v^{(i)}\big)\big\|^2\\ &\gtrsim \frac{\mu_2}{d}\mathbb{E}_{u,v\in V}\big\|f\big(u^{(i)}\big)-f\big(v^{(i)}\big)\big\|^2\\ &\geq \frac{\mu_2}{d}\,\mathbb{E}_{u,v\in V}\,d_G(u,v)^2\\ &\gtrsim \frac{\mu_2}{d}(\log_d m)^2.\end{aligned}$$

In particular, in every layer $i\in[D+1]$, at least one vertical edge $(u^{(i)},v^{(i)})$ has $\|\bar{f}(u^{(i)})-\bar{f}(v^{(i)})\|\gtrsim\sqrt{\frac{\mu_2}{d}}\log_d m$. Therefore the desired result follows from Lemma 3.1. □

We now to come our main theorem.

Theorem 3.4 *If $G=(V,E)$ is a d-regular, m-vertex, vertex-transitive graph with $\mu_2=\mu_2(G)$, then*

$$c_2\big(\widetilde{G}^{\oslash k}\big)\gtrsim\sqrt{\frac{\mu_2 k}{d}}\log_d m.$$

Proof Let $f:V(\widetilde{G}^{\oslash k})\to L_2$ be any noncontracting embedding. The theorem follows almost immediately by induction: Consider the top level copy of $\widetilde{G}$ in $\widetilde{G}^{\oslash k}$ and call it G_0. Let $(x, y) \in E(G_0)$ be the horizontal edge for which $\|f(x) - f(y)\|$ is longest. Clearly this edge spans a copy of $\widetilde{G}^{\oslash k-1}$, which we call G_1. By induction and an application of Lemma 3.3, there exists a (universal) constant $c > 0$ and an edge $(u, v) \in E(G_1)$ such that

$$\begin{aligned}\frac{\|f(u) - f(v)\|^2}{d_{\widetilde{G}^{\oslash k}}(u, v)^2} &\geq \frac{c\mu_2(k-1)}{d}(\log_d m)^2 + \frac{\|f(x) - f(y)\|^2}{d_{\widetilde{G}^{\oslash k}}(x, y)^2}\\ &\geq \frac{c\mu_2(k-1)}{d}(\log_d m)^2 + \frac{c\mu_2}{d}(\log_d m)^2 + \frac{\|f(s) - f(t)\|^2}{d_{\widetilde{G}^{\oslash k}}(s, t)},\end{aligned}$$

completing the proof. □

Corollary 3.5 *If $G = (V, E)$ is an $O(1)$-regular m-vertex, vertex-transitive graph with $\mu_2 = \Omega(1)$, then*

$$c_2\big(\widetilde{G}^{\oslash k}\big) \gtrsim \sqrt{k}\log m \approx \sqrt{\log m \log N},$$

where $N = |V(\widetilde{G}^{\oslash k})| = 2^{\Theta(k \log m)}$.

We remark that infinite families of $O(1)$-regular vertex-transitive graphs with $\mu_2 \geq \Omega(1)$ are well known. In particular, one can take any construction coming from the Cayley graphs of finitely generated groups. We refer to the survey [6]; see, in particular, Margulis' construction in Sect. 8.

3.1 Extension to Other L_p Spaces

Our previous lower bound dealt only with L_2. We now prove the following.

Theorem 3.6 *If $G = (V, E)$ is an $O(1)$-regular m-vertex, vertex-transitive graph with $\mu_2 = \Omega(1)$, then for any $p > 1$, there exists a constant $C(p)$ such that*

$$c_p\big(\widetilde{G}^{\oslash k}\big) \gtrsim C(p)k^{1/q}\log m \approx C(p)(\log m)^{1-1/q}(\log N)^{1/q},$$

where $N = |V(\widetilde{G}^{\oslash k})|$ and $q = \max\{p, 2\}$.

The only changes required are to Lemmas 3.2 and 3.1 (which uses orthogonality). The first can be replaced by Matoušek's [14] Poincaré inequality: If $G = (V, E)$ is an $O(1)$-regular expander graph with $\mu_2 = \Omega(1)$, then for any $p \in [1, \infty)$ and $f : V \to L_p$,

$$\mathbb{E}_{x,y\in V}\big\|f(x) - f(y)\big\|_p^p \leq O(2p)^p \mathbb{E}_{(x,y)\in E}\big\|f(x) - f(y)\big\|_p^p.$$

Generalizing Lemma 3.1 is more involved. We need the following well-known 4-point inequalities for L_p spaces.

Lemma 3.7 *Consider any $p \geq 1$ and $u, v, w, x \in L_p$. If $1 \leq p \leq 2$, then*

$$\|u-w\|_p^2 + (p-1)\|x-v\|_p^2 \leq \|u-v\|_p^2 + \|v-w\|_p^2 + \|x-w\|_p^2 + \|u-x\|_p^2. \quad (5)$$

If $p \geq 2$, then

$$\|u-w\|_p^p + \|x-v\|_p^p \leq 2^{p-2}\big(\|u-v\|_p^p + \|v-w\|_p^p + \|x-w\|_p^p + \|u-x\|_p^p\big). \quad (6)$$

Proof The following inequalities are known for $a, b \in L_p$ (see, e.g., [3]). If $1 \leq p \leq 2$, then

$$\left\|\frac{a+b}{2}\right\|_p^2 + (p-1)\left\|\frac{a-b}{2}\right\|_p^2 \leq \frac{\|a\|_p^2 + \|b\|_p^2}{2}.$$

On the other hand, if $p \geq 2$, then

$$\left\|\frac{a+b}{2}\right\|_p^p + \left\|\frac{a-b}{2}\right\|_p^p \leq \frac{\|a\|_p^p + \|b\|_p^p}{2}.$$

In both cases, the desired 4-point inequalities are obtained by averaging two incarnations of one of the above inequalities with $a = u - v, b = v - w$ and then $a = u - x, b = x - w$ and using the convexity of the L_p norm (see, e.g., [12, Lemma 2.1]). $\square$

Lemma 3.8 *Let G be a vertex transitive graph, and suppose that $p > 1$. If $q = \max\{p, 2\}$, then there exists a constant $K(p) > 0$ such that the following holds. Let $f : V(\widetilde{G}) \to L_p$ be an injective mapping and define $\bar{f} : V(\widetilde{G}) \to L_p$ by*

$$\bar{f}(x) = \frac{1}{|\mathsf{Aut}(G)|^{1/p}}\big(f(\widetilde{\pi}x)\big)_{\pi \in \mathsf{Aut}(G)}.$$

Suppose that β is such that for every $i \in [D+1]$, there exists a vertical edge $(u^{(i)}, v^{(i)})$ which satisfies $\|\bar{f}(u^{(i)}) - \bar{f}(v^{(i)})\|_p \geq \beta$. Then there exists a horizontal edge $(x, y) \in E(\widetilde{G})$ such that

$$\frac{\|\bar{f}(x) - \bar{f}(y)\|_p^q}{d_{\widetilde{G}}(x, y)^q} \geq \frac{\|f(s) - f(t)\|_p^q}{d_{\widetilde{G}}(s, t)^q} + K(p)\beta^q. \quad (7)$$

Proof Let $D = \mathrm{diam}(G)$. For simplicity, we assume that D is even in what follows.

(F1) $\|\bar{f}(s) - \bar{f}(t)\|_p = \|f(s) - f(t)\|_p$.
(F2) For all $u, v \in V$,

$$\big\|\bar{f}(s) - \bar{f}\big(v^{(1)}\big)\big\|_p = \big\|\bar{f}(s) - \bar{f}\big(u^{(1)}\big)\big\|_p,$$
$$\big\|\bar{f}(t) - \bar{f}\big(v^{(D+1)}\big)\big\|_p = \big\|\bar{f}(t) - \bar{f}\big(u^{(D+1)}\big)\big\|_p.$$

(F3) For all $u, v \in V$ and $i \in [D]$,

$$\big\|\bar{f}\big(v^{(i)}\big) - \bar{f}\big(v^{(i+1)}\big)\big\|_p = \big\|\bar{f}\big(u^{(i)}\big) - \bar{f}\big(u^{(i+1)}\big)\big\|_p.$$

Fix some $r \in V$ and let $\rho_0 = \|\bar{f}(s) - \bar{f}(r^{(1)})\|_p$, $\rho_i = \|\bar{f}(r^{(2i-1)}) - \bar{f}(r^{(2i+1)})\|_p$ for $i = 1, \dots, D/2$ and $\rho_{D/2+1} = \|\bar{f}(t) - \bar{f}(r^{(D+1)})\|_p$. Also, let $\rho_{i,1} = \|\bar{f}(r^{(2i-1)}) - \bar{f}(r^{(2i)})\|_p$ and $\rho_{i,2} = \|\bar{f}(r^{(2i)}) - \bar{f}(r^{(2i+1)})\|_p$ for $i = 1, \dots, D/2$.

Note that, by (F2) and (F3) above, the values $\{\rho_i\}$ do not depend on the representative $r \in V$. In this case, we have

$$\sum_{i=0}^{D/2+1} \rho_i \geq \|\bar{f}(s) - \bar{f}(t)\|_p = 9\gamma D, \tag{8}$$

where we put $\gamma = \frac{\|f(s)-f(t)\|_p}{d_{\widetilde{G}}(s,t)}$. Note that $\gamma > 0$ since f is injective.

Let $\delta = \delta(p)$ be a constant to be chosen shortly. Recalling that $d_{\widetilde{G}}(s,t) = 9D$ and $d_{\widetilde{G}}(s, r^{(1)}) = 4D$, observe that if $\rho_0^q \geq (1 + \delta\frac{\beta^q}{\gamma^q})(4\gamma D)^q$, then

$$\max\left(\frac{\|\bar{f}(s) - \bar{f}(s'))\|_p^q}{d_{\widetilde{G}}(s,s')^q}, \frac{\|\bar{f}(s') - \bar{f}(r^{(1)})\|_p^q}{d_{\widetilde{G}}(s',r^{(1)})^q}\right) \geq \gamma^q + \delta\beta^q,$$

verifying (7). The symmetric argument holds for $\rho_{D/2+1}$, and thus we may assume that

$$\rho_0, \rho_{D/2+1} \leq 4\gamma D\left(1 + \delta\frac{\beta^q}{\gamma^q}\right)^{1/q} \leq 4\gamma D\left(1 + \delta\frac{\beta^q}{\gamma^q}\right).$$

Similarly, we may assume that $\rho_{i,1}, \rho_{i,2} \leq \gamma(1 + \delta\frac{\beta^q}{\gamma^q})^{1/q}$ for every $i \in [D/2]$.

In this case, by (8), there must exist an index $j \in \{1, 2, \dots, D/2\}$ such that

$$\rho_j \geq \left(1 - 8\delta\frac{\beta^q}{\gamma^q}\right)2\gamma.$$

Now, consider a vertical edge $(u^{(2j)}, v^{(2j)})$ with $\|f(u^{(2j)}) - f(v^{(2j)})\|_p \geq \beta$. Also, consider the vertices $v^{(2j-1)}$ and $v^{(2j+1)}$. We now replace the use of orthogonality ((F4) in Lemma 3.1) with Lemma 3.7.

We apply one of (5) or (6) of these two inequalities with $x = f(u^{(2j)})$, $v = f(v^{(2j)})$, $u = f(v^{(2j-1)})$, $w = f(v^{(2j+1)})$. In the case $p \geq 2$, we use (5) to conclude that

$$\begin{aligned}
&\|f(u^{(2j)}) - f(v^{(2j-1)})\|_p^p + \|f(u^{(2j)}) - f(v^{(2j+1)})\|_p^p \\
&\quad \geq 2^{-p+2}\rho_j^p + 2^{-q+2}\beta^p - \rho_{j,1}^p - \rho_{j,2}^p \\
&\quad \geq 2\gamma^p + 2^{-p+2}\beta^p - 34\delta p\beta^p.
\end{aligned}$$

Thus choosing $\delta = \frac{2^{1-p}}{34p}$ yields the desired result for one of $(u^{(2j)}, v^{(2j-1)})$ or $(u^{(2j)}, v^{(2j+1)})$.

In the case $1 \leq p \leq 2$, we use (6) to conclude that

$$\begin{aligned}
&\|f(u^{(2j)}) - f(v^{(2j-1)})\|_p^2 + \|f(u^{(2j)}) - f(v^{(2j+1)})\|_p^2 \\
&\quad \geq \rho_j^2 + (p-1)\beta^2 - \rho_{j,1}^2 - \rho_{j,2}^2.
\end{aligned}$$

A similar choice of δ again yields the desired result. $\square$

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