Graph comparison meets Alexandrov

Nina Lebedeva and Anton Petrunin

Abstract

Graph comparison is a certain type of condition on metric space encoded by a finite graph. We show that any nontrivial graph comparison implies one of two Alexandrov's comparisons. The proof gives a complete description of graphs with trivial graph comparisons.

The notion of graph comparison was introduced in [7]. It was studied further in [3–6, 10, 11]. Let us mention some of the results.

- Graph comparisons for the tripod and four-cycle capture nonnegative and nonpositive curvature in the sense of Alexandrov; see below.
- Graph comparison for certain trees is used to formulate a stronger version of the so-called *Lang–Schroeder–Sturm inequality* [2, 5, 9].
- The all-tree comparison gives a metric description of target spaces of submetries from subsets of Hilbert space [7].
- For a certain tree, graph comparison has tight relation with the so-called *MTW condition* that was introduced by Xi-Nan Ma, Neil Trudinger, and Xu-Jia Wang [7, 8].
- Octahedron comparison holds in products of trees [6].

We will show that any nontrivial graph comparison implies one of two Alexandrov's comparisons.

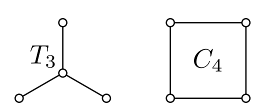
Let us start with the definition. Suppose Γ is a graph with vertices $v_1, \dots, v_n$. We write $v_i \sim v_j$ (or $v_i \nsim v_j$) if v_i is adjacent (respectively nonadjacent) to v_j.

A metric space X meets the Γ-*comparison* if for any n points in X labeled by vertices of Γ there is a model configuration $\tilde{v}_1, \dots, \tilde{v}_n$ in the Hilbert space $\mathbb{H}$ such that

$$\begin{aligned} v_i \sim v_j \quad &\Longrightarrow \quad |\tilde{v}_i - \tilde{v}_j|_{\mathbb{H}} \leqslant |v_i - v_j|_X, \\ v_i \nsim v_j \quad &\Longrightarrow \quad |\tilde{v}_i - \tilde{v}_j|_{\mathbb{H}} \geqslant |v_i - v_j|_X; \end{aligned}$$

here $|\,-\,|_X$ denotes distance in the metric space X. (Note that v_i may refer to a vertex in Γ and to the corresponding point in X.)

Denote by T_3 and C_4 and tripod and four-cycle shown on the diagram. The C_4-comparison is equivalent to nonnegative curvature, and T_3-comparison is equivalent to the nonpositive curvature in the sense of Alexandrov [7]. These definitions are usually applied to length spaces, but they can be applied to general metric spaces; the latter convention is used in [1].

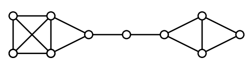


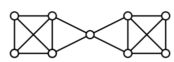
Theorem. *Let Γ be an arbitrary finite graph. Then either Γ-comparison holds in any metric space, or it implies C_4- or T_3-comparison.*

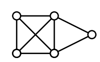
The following corollary describes all graphs Γ with trivial Γ-comparison; it follows from the proof of the theorem.

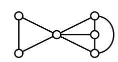
Corollary. *Let Γ be a finite connected graph. Suppose that Γ-comparison is trivial; that is, it holds in any metric space. Then Γ can be constructed from a path P_ℓ of length $\ell \geqslant 0$ and two complete graphs K_{m_1}, K_{m_2} by attaching k_1 vertices of K_{m_1} to the left end of P_ℓ and k_2 vertices of K_{m_2} to the right end of P_ℓ.*

Note that the graph Γ in the corollary is described by five integers (m_1, k_1, ℓ, k_2, m_2) such that $\ell \geqslant 0$, $m_i \geqslant k_i \geqslant 0$, and $k_i > 0$ if $m_i > 0$ for each i. Examples of such graphs and their 5-arrays are shown below.


$(4, 2, 2, 2, 3)$


$(4, 2, 0, 2, 4)$


$(4, 2, 0, 0, 0)$


$(2, 2, 0, 3, 3)$

Proof. Suppose Γ has connected components $\Gamma_1, \dots, \Gamma_k$. Observe that Γ-comparison holds in a metric space X if and only if so does every Γ_i-comparison. Therefore we can assume that Γ is connected.

Suppose Γ is a graph with vertices $v_1, \dots, v_n$ as before. Let e be an edge in Γ; we can assume that it connects v_1 to v_2. Remove v_1 and v_2 from Γ and add a new vertex w such that for any other vertex u we have

- ⋄ if $u \sim v_1$ and $u \sim v_2$, then $u \sim w$;
- ⋄ if $u \nsim v_1$ and $u \nsim v_2$, then $u \nsim w$;
- ⋄ in the remaining cases we can choose arbitrarily $u \sim w$ or $u \nsim w$.

Denote the obtained graph by Γ'.

Applying the definition of Γ-comparison assuming that $v_1 = v_2$ in X, we get the following.

Claim. *If Γ-comparison holds in a metric space X, then so does Γ'-comparison.*

The operation that produces Γ' from Γ will be called *edge shrinking*. If a graph Δ can be obtained from Γ applying edge shrinking several times, then we will write $\Delta \prec \Gamma$.

Note that the claim implies the following two statements:

- ⋄ If Δ is an induced subgraph of a connected finite graph Γ, then $\Delta \prec \Gamma$.
- ⋄ If $\Delta \prec \Gamma$, then Γ-comparison implies Δ-comparison.

Taking all the above into account, we get the following reformulation of the theorem.

Reformulation. *For any finite connected graph Γ*

(a) Γ-comparison holds in any metric space, or

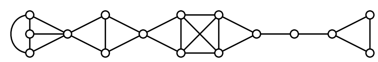
(b) $C_4 \prec \Gamma$, or

(c) $T_3 \prec \Gamma$.

A connected graph will be called *multipath* if it has an integer function ℓ on the set of the vertex set such that v is adjacent to w if and only if

$$|\ell(v) - \ell(w)| \leqslant 1.$$

The value $\ell(w)$ will be called the *level* of the vertex w. Multipath is completely described by a sequence of integers that give the number of vertexes on each level. An example of a multipath with its sequence is shown on the diagram.



$(3, 1, 2, 1, 2, 2, 1, 1, 1, 2)$

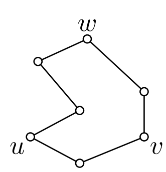
Lemma. *Let Γ be a connected finite graph such that $C_4 \not\prec \Gamma$ and $T_3 \not\prec \Gamma$. Then Γ is a multipath.*

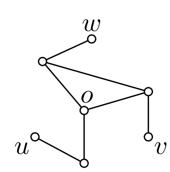
Proof of the lemma. Let us denote by $|\ -\ |_\Gamma$ the path metric on the vertex set of Γ; it is equal to the number of edges in a shortest path connecting two vertices. Note that it is sufficient to show that

$$(*)\ \ |u-w|_\Gamma \geqslant |u-v|_\Gamma \geqslant |v-w|_\Gamma \geqslant 2 \quad \Longrightarrow \quad |u-w|_\Gamma = |u-v|_\Gamma + |v-w|_\Gamma$$

for any three vertices u, v, and w in Γ.

Suppose $(*)$ does not hold for u, v, and w. Let us pass to a minimal connected induced subgraph $\Delta \ni u, v, w$ of Γ such that $(*)$ still does not hold in Δ. Note





that Δ is either a cycle or it has three paths from a vertex, say o, to each of u, v, and w such that each of these paths do not visit the remaining vertices in the triple u, v, w. In these cases, we have $C_4 \prec \Delta$ and $T_3 \prec \Delta$ respectively. By the observation above $\Delta \prec \Gamma$ — the lemma is proved. $\square$

Proposition. *Let Γ be a multipath with sequence $(k_0, \ldots, k_m)$. Suppose $C_4 \not\prec \Gamma$ and $T_3 \not\prec \Gamma$. Then*

(a) If $m \geqslant 4$, then $k_2 = \cdots = k_{m-2} = 1$.
(b) If $m = 3$, then $k_1 = 1$ or $k_2 = 1$.
(c) If $m = 2$, then $k_0 = 1$, $k_1 = 1$, or $k_2 = 1$.

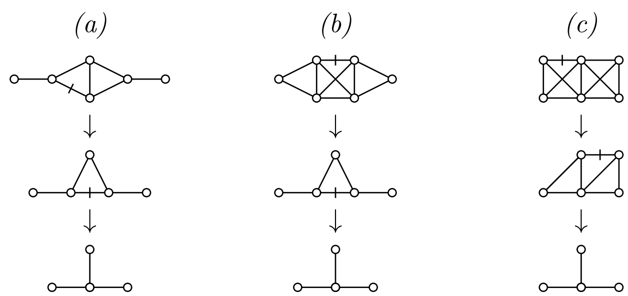
Proof of the proposition. Assuming the contrary in each case we get

(a). If $m \geqslant 4$, then multipath $(1, 1, 2, 1, 1)$ is an induced subgraph of Γ.

(b). If $m = 3$, then multipath $(1, 2, 2, 1)$ is an induced subgraph of Γ.

(c). If $m = 2$, then multipath $(2, 2, 2)$ is an induced subgraph of Γ.

In each case, we arrive at a contradiction by applying edge shrinking to the marked edges as shown on the diagram.



□

It remains to show that Γ-comparison holds in any metric space for every multipath Γ described in 6. This is done by prescribing the coordinates for the needed model configuration on the real line.

Each edge of Γ comes with weight — the distance between the endpoints in X. Define the distance $\|v-w\|_\Gamma$ as the minimal total weight of paths connecting v to w in Γ. Note that

$$\|v - w\|_\Gamma \geqslant |v - w|_X$$

for any v and w.

If $m \leqslant 1$ then Γ is a complete graph. In this case, Γ-comparison is trivial. It remains to consider cases $m \geqslant 2$.

Let us choose a special vertex w that is unique on its level and not too far from the middle of Γ. Namely, if $m \geqslant 4$, then choose w on the second level; by the proposition it is unique on its level. If $m = 3$, then by the proposition we can assume that $k_2 = 1$; in this case choose w on the second level. Finally, if $m = 2$, let w be any vertex that is unique on its level; it exists by the proposition.

For every vertex v_i, let

$$\tilde{v}_i = \pm\|w - v_i\|_\Gamma,$$

where the sign is plus if v_i has a higher level than w and minus otherwise. By the triangle inequality, the obtained configuration $\tilde{v}_1, \dots, \tilde{v}_n$ meets the condition of Γ-comparison. □

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