

Homework assignments

Due 2023-03-02: 1.6, 1.7, 1.9, 1.10, 1.14.

Due 2023-03-09: 1.13, 2.3, 2.5, 2.7, 2.8.

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Lecture 1

Alexandrov embedding theorem

This lecture contains selected material from Alexandrov's book [2].

We give a proof of the Cauchy theorem and then modify it to prove the Alexandrov uniqueness theorem. Further, we sketch a proof of the Alexandrov embedding theorem.

A Cauchy theorem

Further, surfaces of convex polyhedrons will be considered with intrinsic metric; it is defined as the length of a shortest path on the surface between points. Shortest paths parametrized by arclength will be called geodesics; this term has a slightly different meaning in Riemannian geometry.

1.1. Theorem. *Let K and K' be two non-degenerate convex polyhedrons in \mathbb{E}^3 ; denote their surfaces by P and P' . Suppose there is an isometry $P \rightarrow P'$ that sends each face of K to a face of K' . Then K is congruent to K' .*

Proof. Consider the graph Γ formed by the edges of K ; the edges of K' form the same graph.

For an edge e in Γ , denote by α_e and α'_e the corresponding dihedral angles in K and K' respectively. Mark e by plus if $\alpha_e < \alpha'_e$ and by minus if $\alpha_e > \alpha'_e$.

Now remove from Γ everything which was not marked; that is, leave only the edges marked by (+) or (−) and their endpoints.

Note that the theorem follows if Γ is an empty graph; assume the contrary.

The graph Γ is embedded into P , which is homeomorphic to the sphere. In particular, the edges coming from one vertex have a natural cyclic order. Given a vertex v of Γ , count the number of sign changes around v ; that is, the number of consequent pairs edges with different signs.

1.2. Local lemma. *For any vertex of Γ the number of sign changes is at least 4.*

In other words, at each vertex of Γ , one can choose 4 edges marked by $(+)$, $(-)$, $(+)$, $(-)$ in the same cyclical order. Note that the local lemma contradicts the following.

1.3. Global lemma. *Let Γ be a nonempty subgraph of the graph formed by the edges of a convex polyhedron. Then it is impossible to mark all of the edges of Γ by $(+)$ or $(-)$ such that the number of sign changes around each vertex of Γ is at least 4.*

It remains to prove these two lemmas. □

B Local lemma

Next lemma is the main ingredient in our proof of the local lemma.

1.4. Arm lemma. *Assume that $A = [a_0 a_1 \dots a_n]$ is a convex polygon in \mathbb{E}^2 and $A' = [a'_0 a'_1 \dots a'_n]$ be a polygonal line in \mathbb{E}^3 such that*

$$|a_i - a_{i+1}| = |a'_i - a'_{i+1}|$$

for any $i \in \{0, \dots, n-1\}$ and

$$\angle a_i \leq \angle a'_i$$

for each $i \in \{1, \dots, n-1\}$. Then

$$|a_0 - a_n| \leq |a'_0 - a'_n|$$

and equality holds if and only if A is congruent to A' .

One may view the polygonal lines $[a_0 a_1 \dots a_n]$ and $[a'_0 a'_1 \dots a'_n]$ as a robot's arm in two positions. The arm lemma states that when the arm opens, the distance between the shoulder and tips of the fingers increases.

1.5. Exercise. *Show that the arm lemma does not hold if instead of the convexity, one only the local convexity; that is, if you go along the polygonal line $a_0 a_1 \dots a_n$, then you only turn left.*

1.6. Exercise. Suppose $A = [a_1 \dots a_n]$ and $A' = [a'_1 \dots a'_n]$ be non-congruent convex plane polygons with equal corresponding sides. Mark each vertex a_i with plus (minus) if the interior angle of A at a_i is smaller (respectively bigger) than the interior angle of A' at a'_i . Show that there are at least 4 sign changes around A .

Give an example showing the statement does not hold without assuming convexity.

In the proof, we will use the following exercise which is the triangle inequality angles (or the spherical triangle inequality).

1.7. Exercise. Let w_1, w_2, w_3 be unit vectors in \mathbb{E}^3 . Denote by $\theta_{i,j}$ the angle between the vectors v_i and v_j . Show that

$$\theta_{1,3} \leq \theta_{1,2} + \theta_{2,3}$$

and in case of equality, the vectors w_1, w_2, w_3 lie in a plane.

Proof. We will view \mathbb{E}^2 as the xy -plane in \mathbb{E}^3 ; so both A and A' lie in \mathbb{E}^3 . Let a_m be the vertex of A that lies on the maximal distance to the line $(a_0 a_n)$.

Let us shift indexes of a_i and a'_i down by m , so that

$$\begin{array}{lllll} a_{-m} := a_0, & \dots & a_0 := a_m, & \dots & a_k := a_n, \\ a'_{-m} := a'_0, & \dots & a'_0 := a'_m, & \dots & a'_k := a'_n, \end{array}$$

where $k = n - m$. (Here the symbol “:=” means an assignment as in programming.)

Without loss of generality, we may assume that

- ◇ $a_0 = a'_0$ and they both coincide with the origin $(0, 0, 0) \in \mathbb{E}^3$;
- ◇ all a_i lie in the xy -plane and the x -axis is parallel to the line $(a_{-m} a_k)$;
- ◇ the angle $\angle a'_0$ lies in xy -plane and contains the angle $\angle a_0$ inside and the directions to a'_{-1}, a_{-1} , a_1 and a'_1 from a_0 appear in the same cyclic order.

Denote by x_i and x'_i the projections of a_i and a'_i to the x -axis. We can assume in addition that $x_k \geq x_{-m}$. In this case,

$$|a_k - a_{-m}| = x_k - x_{-m}.$$

Since the projection is a distance non-expanding, we also have

$$|a'_k - a'_{-m}| \geq x'_k - x'_{-m}.$$

Therefore it is sufficient to show that

$$x'_k - x'_{-m} \geq x_k - x_{-m}.$$

The latter holds if

$$\textcircled{1} \quad x'_i - x'_{i-1} \geq x_i - x_{i-1}.$$

for each i . It remains to prove $\textcircled{1}$.

Let us assume that $i > 0$; the case $i \leq 0$ is similar. Denote by σ_i (σ'_i) the angle between the vector $w_i = a_i - a_{i-1}$ (respectively $w'_i = a'_i - a'_{i-1}$) and the x -axis. Note that

$$\begin{aligned} \textcircled{2} \quad x_i - x_{i-1} &= |a_i - a_{i-1}| \cdot \cos \sigma_i, \\ x'_i - x'_{i-1} &= |a_i - a_{i-1}| \cdot \cos \sigma'_i \end{aligned}$$

for each $i > 0$. By construction $\sigma_1 \geq \sigma'_1$. Note that $\angle(w_{i-1}, w_i) = \pi - \angle a_i$. From convexity of $[a_1 a_1 \dots a_i]$, we have

$$\sigma_i = \sigma_1 + (\pi - \angle a_1) + \dots + (\pi - \angle a_i)$$

for any $i > 0$. Since $\angle(w'_{i-1}, w'_i) = \pi - \angle a'_i$, applying 1.7 several times, we get

$$\sigma'_i \leq \sigma'_1 + (\pi - \angle a'_1) + \dots + (\pi - \angle a'_i).$$

Since $\angle a'_j \geq \angle a_j$ for each j , we get $\sigma'_i \leq \sigma_i$, and therefore

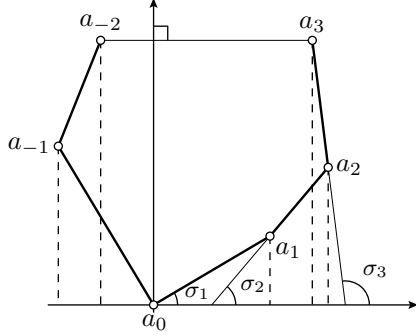
$$\cos \sigma'_i \geq \cos \sigma_i$$

Applying $\textcircled{2}$, we get $\textcircled{1}$.

In the case of equality, we have $\sigma_i = \sigma'_i$, which implies $\angle a_i = \angle a'_i$ for each i . This also implies that all a'_i lie in xy -plane. The latter easily follows from the equality case in 1.7. \square

Proof of the local lemma (1.2). Assume that the local lemma does not hold at the vertex v of Γ . Cut from P a small pyramid Δ with the vertex v . One can choose two points a and b on the base of Δ so that on one side of the segments $[va]$ and $[vb]$ we have only pluses and on the other side only minuses.

The base of Δ has two polygonal lines with ends at a and b . Choose the one that has only pluses; denote it by $a_0 a_1 \dots a_n$; so $a = a_0$ and $b = a_n$. Denote by $a'_0 a'_1 \dots a'_n$ the corresponding line in P' ; let $a' = a'_0$ and $b' = a'_n$.



Since each marked edge passing thru a_i has a (+) on it or nothing, we have

$$\angle a_i \leq \angle a'_i$$

for each i .

1.8. Exercise. *Prove the last statement.*

By the construction we have $|a_i - a_{i-1}| = |a'_i - a'_{i-1}|$ for all i . By the arm lemma (1.4), we get

$$\textcircled{3} \quad |a - b| \leq |a' - b'|.$$

Swap K and K' and repeat the same construction. We get

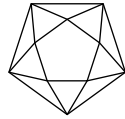
$$\textcircled{4} \quad |a - b| \geq |a' - b'|.$$

The claims $\textcircled{3}$ and $\textcircled{4}$ together imply $|a - b| = |a' - b'|$. The equality case in the arm lemma implies that no edge at v is marked; that is, v is not a vertex of Γ — a contradiction. \square

From the proof, it follows that the local lemma is indeed local — it works for two noncongruent convex polyhedral angles with equal corresponding faces. Use this observation to solve the following exercise.

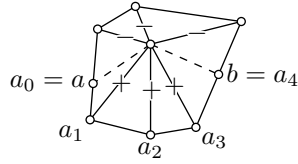
1.9. Exercise. *Consider two polyhedral discs in \mathbb{E}^3 glued from regular polygons by the rule on the diagrams. Assume that each disc is part of a surface of a convex polyhedron.*

- (a) *The first configuration is rigid; that is, one can not fix the position of the pentagon and continuously move the remaining 5 vertices in a new position so that each triangle moves by a one-parameter family of isometries of \mathbb{E}^3 .*
- (b) *Show that the second configuration has a rotational symmetry with the axis passing thru the midpoint of the marked edge.*



C Global lemma

The proof of the global lemma is based on counting the sign changes in two ways; first while moving around each vertex of Γ and second while moving around each of the regions separated by Γ on the surface P . If two edges are adjacent at a vertex, then they are also adjacent in a region. The converse is true as well. Therefore, both countings give the same number.



It is instructive to do the next exercise before diving into the proof.

1.10. Exercise. *Try to mark the edges of an octahedron by pluses and minuses such that there would be 4 sign changes at each vertex.*

Show that this is impossible.

Proof of 1.3. We can assume that Γ is connected; that is, one can get from any vertex to any other vertex by walking along edges. (If not, pass to a connected component of Γ .)

Denote by k and l the number of vertices and edges in Γ . Denote by m the number of regions that Γ cuts from P . Since Γ is connected, each region is homeomorphic to an open disc.

1.11. Exercise. *Prove the last statement.*

Now we can apply Euler's formula

$$\textcircled{1} \quad k - l + m = 2.$$

Denote by s the total number of sign changes in Γ for all vertices. By the local lemma (1.2), we have

$$\textcircled{2} \quad 4 \cdot k \leq s.$$

Let us get an upper bound on s by counting the number of sign changes when you go around each region. Denote by m_n the number of regions bounded by n edges; if an edge appears twice when it is counted twice. Note that each region is bounded by at least 3 edges; therefore

$$\textcircled{3} \quad m = m_3 + m_4 + m_5 + \dots$$

Counting edges and using the fact that each edge belongs to exactly two regions, we get

$$2 \cdot l = 3 \cdot m_3 + 4 \cdot m_4 + 5 \cdot m_5 + \dots$$

Combining this with Euler's formula ($\textcircled{1}$), we get

$$\textcircled{4} \quad 4 \cdot k = 8 + 2 \cdot m_3 + 4 \cdot m_4 + 6 \cdot m_5 + 8 \cdot m_6 + \dots$$

Observe that the number of sign changes in n -gon regions has to be even and $\leq n$. Therefore

$$\textcircled{5} \quad s \leq 2 \cdot m_3 + 4 \cdot m_4 + 4 \cdot m_5 + 6 \cdot m_6 + \dots$$

Clearly, $\textcircled{2}$ and $\textcircled{5}$ contradict $\textcircled{4}$. □

D Uniqueness

Alexandrov's uniqueness theorem states that the conclusion of the Cauchy theorem (1.1) still holds without the face-to-face assumption.

1.12. Theorem. *Any two convex polyhedrons in \mathbb{E}^3 with isometric surfaces are congruent.*

Needed modifications in the proof of 1.1. Suppose $\iota: P \rightarrow P'$ be an isometry between surfaces of K and K' . Mark in P all the edges of K and all the inverse images of edges in K' ; further, these will be called fake edges. The marked lines divide P into convex polygons, and the restriction of ι to each polygon is a rigid motion. These polygons play the role of faces in the proof above.

A vertex of the obtained graph can be a vertex of K or it can be a fake vertex; that is, it might be an intersection of an edge and a fake edge.



For the first type of vertex, the local lemma can be proved the same way. For a fake vertex v , it is easy to see that both parts of the edge coming thru v are marked with minus while both of the fake edges at v are marked with plus. Therefore, the local lemma holds for the fake vertices as well.

What remains in the proof needs no modifications. \square

1.13. Exercise. *Let K be a convex polyhedron in \mathbb{E}^3 ; denote by P its surface. Show that each isometry $\iota: P \rightarrow P$, can be extended to an isometry of \mathbb{E}^3 .*

E Existence

Let P be a surface with a polyhedral metric. The curvature of a point $p \in P$ is defined as $2 \cdot \pi - \theta$, where θ is the total angle around p .

1.14. Exercise. *Suppose P is the surface of a convex polyhedron. Show that P is homeomorphic to the sphere, and it has nonnegative curvature at every point.*

1.15. Exercise. Assume that the surface of a nonregular tetrahedron T has curvature π at each of its vertices. Show that

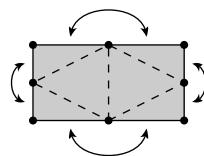
- (a) all faces of T are congruent;
- (b) the line passing thru midpoints of opposite edges of T intersects these edges at right angles.

Alexandrov's theorem states that the converse holds if one includes in the consideration twice covered polygons. In other words, we assume that a polyhedron can degenerate to a plane polygon; in this case, its surface is defined as two copies of the polygon glued along the boundaries. Intuitively, one can regard these copies as different sides of the polygon. To get from one side to the other one has to cross the boundary of the polygon.

1.16. Theorem. A polyhedral metric on the sphere is isometric to the surface of a convex polyhedron (possibly degenerate) if and only if it has nonnegative curvature at each point.

By 1.12, a convex polyhedron is completely defined by the intrinsic metric of its surface. By 1.16, it follows that knowing the metric we could find the position of the edges. However, in practice, it is not easy to do.

For example, the surface glued from a rectangle as shown on the diagram defines a tetrahedron. Some of the glued lines appear inside facets of the tetrahedron and some edges (dashed lines) do not follow the sides of the rectangle.



Space of polyhedrons. Let us denote by \mathbf{K} the space of all convex polyhedrons in the Euclidean space, including polyhedrons that degenerate to a plane polygon. Polyhedra in \mathbf{K} will be considered up to a motion of the space, and the whole space \mathbf{K} will be considered with the natural topology (so far an intuitive meaning of closeness of two polyhedrons should be sufficient).

Further, denote by \mathbf{K}_n the polyhedrons in \mathbf{K} with exactly n vertices. Since any polyhedron has at least 3 vertices, the space \mathbf{K} admits a subdivision into a countable number of subsets $\mathbf{K}_3, \mathbf{K}_4, \dots$

Space of polyhedral metrics. The space of polyhedral metrics on the sphere with nonnegative curvature will be denoted by \mathbf{P} . The metrics in \mathbf{P} will be considered up to an isometry, and the whole space \mathbf{P} will be equipped with the natural topology (again, an intuitive meaning of closeness of two metrics is sufficient).

A point on the sphere with positive curvature will be called an essential vertex. The subset of \mathbf{P} of all metrics with exactly n essential vertices will be denoted by \mathbf{P}_n . It is easy to see that any metric in \mathbf{P} has at least 3 essential vertices. Therefore \mathbf{P} is subdivided into countably many subsets $\mathbf{P}_3, \mathbf{P}_4, \dots$

From a polyhedron to its surface. By 1.14, passing from a polyhedron to its surface defines a map

$$\iota: \mathbf{K} \rightarrow \mathbf{P}.$$

Note that the number of vertices of a polyhedron is equal to the number of essential vertices on its surface. In other words, $\iota(\mathbf{K}_n) \subset \mathbf{P}_n$ for any $n \geq 3$.

Using the introduced notation, we can unite 1.12 and 1.16 in the following statement.

1.17. Reformulation. *For any integer $n \geq 3$, the map ι induces a bijection between \mathbf{K}_n and \mathbf{P}_n .*

The proof is based on a construction of a one-parameter family of polyhedrons that starts at an arbitrary polyhedron and ends at a polyhedron with its surface isometric to the given one. This type of argument is called the continuity method; it is often used in the theory of differential equations.

Sketch. By 1.12, the map $\iota: \mathbf{K}_n \rightarrow \mathbf{P}_n$ is injective. Let us prove that it is surjective.

1.18. Lemma. *For any integer $n \geq 3$, the space \mathbf{P}_n is connected.*

The proof of this lemma is not complicated, but it requires ingenuity; it can be done by the direct construction of a one-parameter family of metrics in \mathbf{P}_n that connects two given metrics. Such a family can be obtained by a sequential application of the following construction and its inverse.

Let $P \in \mathbf{P}_n$. Suppose v and w are essential vertices in P . Let us cut P along a geodesic from v to w . Note that the geodesic cannot pass thru an essential vertex of P . Further, note that there is a three-parameter family of patches that can be used to patch the cut so that the obtained metric remains in \mathbf{P}_n ; in particular, the obtained metric has exactly n essential vertices (after the patching, the vertices v and w may become inessential).

1.19. Lemma. *The map $\iota: \mathbf{K}_n \rightarrow \mathbf{P}_n$ is open, that is, it maps any open set in \mathbf{K}_n to an open set in \mathbf{P}_n .*

In particular, for any $n \geq 3$, the image $\iota(\mathbf{K}_n)$ is open in \mathbf{P}_n .

This statement is very close to the so-called invariance of domain theorem; the latter states that a continuous injective map between manifolds of the same dimension is open.

Recall that ι is injective. The proof of the invariance of domain theorem can be adapted to our case since both spaces \mathbf{K}_n and \mathbf{P}_n are $(3 \cdot n - 6)$ -dimensional and both look like manifolds, altho, formally speaking, they are *not* manifolds. In a more technical language, \mathbf{K}_n and \mathbf{P}_n have the natural structure of $(3 \cdot n - 6)$ -dimensional orbifolds, and the map ι respects the orbifold structure.

We will only show that both spaces \mathbf{K}_n and \mathbf{P}_n are $(3 \cdot n - 6)$ -dimensional.

Choose $K \in \mathbf{K}_n$. Note that K is uniquely determined by the $3 \cdot n$ coordinates of its n vertices. We can assume that the first vertex is the origin, the second has two vanishing coordinates and the third has one vanishing coordinate; therefore, all polyhedrons in \mathbf{K}_n that lie sufficiently close to K can be described by $3 \cdot n - 6$ parameters. If K has no symmetries, then this description can be made one-to-one; in this case, a neighborhood of K in \mathbf{K}_n is a $(3 \cdot n - 6)$ -dimensional manifold. If K has a nontrivial symmetry group, then this description is not one-to-one but it does not have an impact on the dimension of \mathbf{K}_n .

The case of polyhedral metrics is analogous. We need to construct a subdivision of the sphere into plane triangles using only essential vertices. By Euler's formula, there are exactly $3 \cdot n - 6$ edges in this subdivision. Note that the lengths of edges completely describe the metric, and slight changes in these lengths produce a metric with the same property. Again, if P has no symmetries, then this description is one-to-one.

1.20. Lemma. *The map $\iota: \mathbf{K}_n \rightarrow \mathbf{P}_n$ is closed; that is, the image of a closed set in \mathbf{K}_n is closed in \mathbf{P}_n .*

In particular, for any $n \geq 3$, the set $\iota(\mathbf{K}_n)$ is closed in \mathbf{P}_n .

Choose a closed set Z in \mathbf{K}_n . Denote by \bar{Z} the closure of Z in \mathbf{K} ; note that $Z = \mathbf{K}_n \cap \bar{Z}$. Assume $K_1, K_2, \dots \in Z$ is a sequence of polyhedrons that converges to a polyhedron $K_\infty \in \bar{Z}$. Note that $\iota(K_n)$ converges to $\iota(K_\infty)$ in \mathbf{P} . In particular, $\iota(\bar{Z})$ is closed in \mathbf{P} .

Since $\iota(\mathbf{K}_n) \subset \mathbf{P}_n$ for any $n \geq 3$, we have $\iota(Z) = \iota(\bar{Z}) \cap \mathbf{P}_n$; that is, $\iota(Z)$ is closed in \mathbf{P}_n .

Summarizing, $\iota(\mathbf{K}_n)$ is a nonempty closed and open set in \mathbf{P}_n , and \mathbf{P}_n is connected for any $n \geq 3$. Therefore, $\iota(\mathbf{K}_n) = \mathbf{P}_n$; that is, $\iota: \mathbf{K}_n \rightarrow \mathbf{P}_n$ is surjective. \square

F Comments

In Euclid's Elements, solids were called equal if the same holds for their faces, but no proof was given. Adrien-Marie Legendre became interested in this problem towards the end of the 18th century. He discussed it with his colleague Joseph-Louis Lagrange, who suggested this problem to Augustin-Louis Cauchy in 1813; soon he proved it [5]. This theorem is included in many popular books [1, 6, 10].

The observation that the face-to-face condition can be removed was made by Alexandr Alexandrov [3].

Arm lemma. Original Cauchy's proof [5] also used a version of the arm lemma, but its proof contained a small mistake (corrected in one century).

Our proof of the arm lemma is due to Stanisław Zaremba. This and a couple of other proofs can be found in the letters between him and Isaac Schoenberg [9].

The following variation of the arm lemma makes sense for nonconvex spherical polygons. It is due to Viktor Zalgaller [12]. It can be used instead of the standard arm lemma.

1.21. Another arm lemma. *Let $A = [a_1 \dots a_n]$ and $A' = [a'_1 \dots a'_n]$ be two spherical n -gons (not necessarily convex). Assume that A lies in a half-sphere, the corresponding sides of A and A' are equal and each angle of A is at least the corresponding angle in A' . Then A is congruent to A' .*

Global lemma. A more visual proof of the global lemma is given in [2, II §1.3].

Existence theorem. This theorem was proved by Alexandr Alexandrov [3]. Our sketch is taken from [7]; a complete proof is nicely written in [2]. A very different proof was found by Yuri Volkov in his thesis [11]; it uses a deformation of three-dimensional polyhedral space.

Lecture 2

Nonnegative curvature: definition

A Distances and geodesics

Distances. The distance between two points x and y in a metric space \mathcal{X} will be denoted by $|x - y|$ or $|x - y|_{\mathcal{X}}$. The latter notation is used if we need to emphasize that the distance is taken in the space \mathcal{X} . The function $(x, y) \mapsto |x - y|_{\mathcal{X}}$ is called metric; it has to meet the following conditions for any three points $x, y, z \in \mathcal{X}$:

- (a) $|x - y|_{\mathcal{X}} \geq 0$,
- (b) $|x - y|_{\mathcal{X}} = 0 \iff x = y$,
- (c) $|x - y|_{\mathcal{X}} = |y - x|_{\mathcal{X}}$,
- (d) $|x - y|_{\mathcal{X}} + |y - z|_{\mathcal{X}} \geq |x - z|_{\mathcal{X}}$.

Geodesics. Let \mathbb{I} be a real interval. A distance-preserving map γ from \mathbb{I} to a metric space \mathcal{X} is called a geodesic¹; in other words, $\gamma: \mathbb{I} \rightarrow \mathcal{X}$ is a geodesic if

$$|\gamma(s) - \gamma(t)|_{\mathcal{X}} = |s - t|$$

for any pair $s, t \in \mathbb{I}$.

If $\gamma: [a, b] \rightarrow \mathcal{X}$ is a geodesic such that $p = \gamma(a)$, $q = \gamma(b)$, then we say that γ is a geodesic from p to q . In this case, the image of γ is denoted by $[pq]$, and, with abuse of notations, we also call it a

¹Others call it differently: *shortest path*, *minimizing geodesic*. Also, note that the meaning of the term *geodesic* is different from what is used in Riemannian geometry, altho they are closely related.

geodesic. We may write $[pq]_{\mathcal{X}}$ to emphasize that the geodesic $[pq]$ is in the space \mathcal{X} .

In general, a geodesic from p to q need not exist and if it exists, it need not be unique. However, once we write $[pq]$ we assume that we have chosen such geodesic.

Geodesic path. A geodesic path is a geodesic with constant-speed parameterization by the unit interval $[0, 1]$.

Geodesic space. A metric space is called geodesic if any pair of its points can be joined by a geodesic.

B Triangles, hinges, and angles

Triangles. Given a triple of points p, q, r in a metric space \mathcal{X} , a choice of geodesics $([qr], [rp], [pq])$ will be called a triangle; we will use the short notation $[pqr] = [pqr]_{\mathcal{X}} = ([qr], [rp], [pq])$.

Given a triple $p, q, r \in \mathcal{X}$ there may be no triangle $[pqr]$ simply because one of the pairs of these points cannot be joined by a geodesic. Also, many different triangles with these vertices may exist, any of which can be denoted by $[pqr]$. If we write $[pqr]$, it means that we have chosen such a triangle.

Model triangles. Given three points p, q, r in a metric space \mathcal{X} , let us define its model triangle $[\tilde{p}\tilde{q}\tilde{r}]$ (briefly, $[\tilde{p}\tilde{q}\tilde{r}] = \tilde{\Delta}(pqr)_{\mathbb{E}^2}$) to be a triangle in the Euclidean plane \mathbb{E}^2 such that

$$|\tilde{p} - \tilde{q}|_{\mathbb{E}^2} = |p - q|_{\mathcal{X}}, \quad |\tilde{q} - \tilde{r}|_{\mathbb{E}^2} = |q - r|_{\mathcal{X}}, \quad |\tilde{r} - \tilde{p}|_{\mathbb{E}^2} = |r - p|_{\mathcal{X}}.$$

The same way we can define the hyperbolic and the spherical model triangles $\tilde{\Delta}(pqr)_{\mathbb{H}^2}$, $\tilde{\Delta}(pqr)_{\mathbb{S}^2}$ in the Lobachevsky plane \mathbb{H}^2 and the unit sphere \mathbb{S}^2 . In the latter case, the model triangle is said to be defined if in addition

$$|p - q| + |q - r| + |r - p| < 2 \cdot \pi.$$

In this case, the model triangle again exists and is unique up to an isometry of \mathbb{S}^2 .

Model angles. If $[\tilde{p}\tilde{q}\tilde{r}] = \tilde{\Delta}(pqr)_{\mathbb{E}^2}$ and $|p - q|, |p - r| > 0$, the angle measure of $[\tilde{p}\tilde{q}\tilde{r}]$ at \tilde{p} will be called the model angle of the triple p, q, r and will be denoted by $\tilde{\angle}(p \frac{q}{r})_{\mathbb{E}^2}$. The same way we define $\tilde{\angle}(p \frac{q}{r})_{\mathbb{H}^2}$ and $\tilde{\angle}(p \frac{q}{r})_{\mathbb{S}^2}$; in the latter case we assume in addition that the model triangle $\tilde{\Delta}(pqr)_{\mathbb{S}^2}$ is defined.

We may use the notation $\tilde{\angle}(p \frac{q}{r})$ if it is evident which of the model spaces \mathbb{H}^2 , \mathbb{E}^2 or \mathbb{S}^2 is meant.

Hinges. Let $p, x, y \in \mathcal{X}$ be a triple of points such that p is distinct from x and y . A pair of geodesics $([px], [py])$ will be called a hinge and will be denoted by $[p_y^x] = ([px], [py])$.

C Baby Toponogov

Recall that polyhedral space is a geodesic space that admits a finite triangulation such that each simplex is isometric to a simplex in a Euclidean space. If, in addition, it is homeomorphic to a surface (without boundary), then it is called a polyhedral surface. A point on a polyhedral surface with nonzero curvature is called an essential vertex. Any other point on the surface will be called regular. Note that *any regular point has a neighborhood that is isometric to an open set in the Euclidean plane*.

2.1. Exercise. Let P be a non-negatively curved polyhedral surface.

- (a) Show that a geodesic in P cannot pass thru an essential vertex.
- (b) Show that if two geodesics in P intersect at two points, then these are the endpoints for both geodesics.

The next theorem gives a global geometric property of non-negatively curved polyhedral surface.

Given a hinge $[p_y^x]$ in a polyhedral surface P , denote by $\angle[p_y^x]$ the minimal angle that the hinge cuts from P at p . (Soon we will give a more general definition of $\angle[p_y^x]$.)

2.2. Theorem. Let P be a polyhedral surface. Assume P has non-negative curvature at each point (see 1E). Then

$$\angle[p_y^x] \geq \tilde{\angle}(p_y^x)$$

for any hinge $[p_y^x]$ in P .

The following exercise will be used in the proof.

2.3. Exercise. Let $f: [0, \ell] \rightarrow \mathbb{R}$ be a continuous function such that for any $t \in]0, \ell[$ there is a linear function h that locally supports f from above; that is, $h(t_0) = f(t_0)$, and there is $\varepsilon > 0$ such that $h(t) \geq f(t)$ if $|t - t_0| < \varepsilon$. Show that f is concave.

Proof. Let $[pxy]$ be a triangle in P and let $[\tilde{p}\tilde{x}\tilde{y}]$ be the model triangle of $[pxy]$. Set $\ell = |x - y|_P = |\tilde{x} - \tilde{y}|_{\mathbb{E}^2}$.

Denote by $\gamma(t)$ and $\tilde{\gamma}(t)$ the geodesics $[xy]$ and $[\tilde{x}\tilde{y}]$ parametrized by length starting from x and \tilde{x} , respectively. Observe that it is sufficient to show that

❶

$$|p - \gamma(t)| \leq |\tilde{p} - \tilde{\gamma}(t)|$$

for any t in $[0, \ell]$.

We may assume that p is a regular point; otherwise, move it slightly and apply approximation.

From the cosine law, we get that the function

$$\tilde{f}(t) = |\tilde{p} - \tilde{\gamma}(t)|^2 - t^2$$

is linear. Consider the function

$$f(t) = |p - \gamma(t)|^2 - t^2.$$

Note that $f(0) = \tilde{f}(0)$, $f(\ell) = \tilde{f}(\ell)$, and the inequality ❶ is equivalent to

$$\text{❷} \quad f(t) \geq \tilde{f}(t).$$

By Jensen's inequality, ❷ holds if f is concave.

By 2.1, $\gamma(t_0)$ is regular. Since p is regular, a geodesic $[p\gamma(t)]$ contains only regular points. Therefore for small $\varepsilon > 0$, the ε -neighborhood of $[p\gamma(t)]$, say Ω , contains only regular points. We may assume that Ω is homeomorphic to a disc; in this case, there is a locally distance preserving embedding $\iota: \Omega \rightarrow \mathbb{E}^2$. Note the image $\iota[p\gamma(t)]$ is a line segment that and $\iota(\Omega)$ is the ε -neighborhood of $\iota[p\gamma(t)]$ in \mathbb{E}^2 ; in particular, $\iota(\Omega)$ is convex. Thus $\iota(\Omega)$ contains a triangle with base $\iota[\gamma(t_0 - \varepsilon) \gamma(t_0 + \varepsilon)]$ and vertex $\iota(p)$.

Clearly, for any $t \in [t_0 - \varepsilon, t_0 + \varepsilon]$ we have

$$|\iota(p) - \iota(\gamma(t))| \geq |p - \gamma(t)|.$$

Note that the function

$$h(t) = |\iota(p) - \iota(\gamma(t))|^2 - t^2$$

is linear. From above, h supports f locally at t_0 . It remains to apply 2.3. \square

D Definition

2.4. Definition. A metric space \mathcal{X} has nonnegative curvature in the sense of Alexandrov (briefly, $\mathcal{X} \in \text{CBB}(0)$) if the inequality

$$\text{❶} \quad \tilde{\Delta}(p_x^x)_{\mathbb{E}^2} + \tilde{\Delta}(p_z^y)_{\mathbb{E}^2} + \tilde{\Delta}(p_x^z)_{\mathbb{E}^2} \leq 2 \cdot \pi$$

holds for any quadruple $p, x, y, z \in \mathcal{X}$ such that p is distinct from x, y , and z .

The inequality ❶ is called $\text{CBB}(0)$ comparison for the quadruple p, x, y, z . If instead of \mathbb{E}^2 , we use \mathbb{S}^2 or \mathbb{H}^2 , then we get the definition of $\text{CBB}(1)$ and $\text{CBB}(-1)$ comparisons.

While this definition can be applied to any metric space, it is usually applied to geodesic spaces (or, at least, length spaces that will be defined later).

2.5. Exercise. Show that a polyhedral surface is $\text{CBB}(0)$ if and only if it has nonnegative curvature in the sense of 1E.

The following theorem generalizes 1.12 and 1.16.

2.6. Theorem. A metric space \mathcal{X} is isometric to the surface of a convex body in the Euclidean space if and only if \mathcal{X} is a geodesic $\text{CBB}(0)$ space that is homeomorphic to \mathbb{S}^2 .

Moreover, \mathcal{X} determines the convex body up to congruence.

As before, a convex body can degenerate to a plane figure F ; in this case, its surface is defined as two copies of F glued along the boundary.

The main part is due to Alexandr Alexandov [4]; its proof is an application of 1.16 together with approximation. The last part is very difficult; it was proved by Aleksei Pogorelov [8].

Eventually, we will prove the only-if part of the theorem, which is the simplest part of the theorem; it requires only 1.14 which is the only-if part of 1.16. To do this we will need to introduce the convergence of subsets in Euclidean space (Hausdorff convergence) and convergence of metric spaces (Gromov–Hausdorff convergence); it will be done in the next lecture.

2.7. Exercise. Show that a metric space \mathcal{X} is $\text{CBB}(0)$ if for any quadruple of points $p, x_1, x_2, x_3 \in \mathcal{X}$ there is a quadruple of points $q, y_1, y_2, y_3 \in \mathbb{E}^2$ such that

$$|p - x_i|_{\mathcal{X}} \geq |q - y_i|_{\mathbb{E}^2} \quad \text{and} \quad |x_i - x_j|_{\mathcal{X}} \leq |y_i - y_j|_{\mathbb{E}^2}$$

for all i and j .

2.8. Exercise. Show that \mathbb{R}^2 with metric induced by a norm is $\text{CBB}(0)$ if and only if it is isometric to the Euclidean plane \mathbb{E}^2 .

E Four-point metric spaces

Let us give a more conceptual way to think about the comparison inequality in 2.4 and an analogous inequality for upper curvature bound that will appear later.

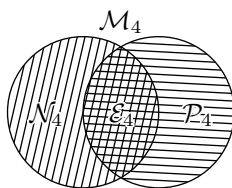
Consider the space \mathcal{M}_4 of all isometry classes of 4-point metric spaces. Each element in \mathcal{M}_4 can be described by 6 numbers — the distances between all 6 pairs of its points, say $\ell_{i,j}$ for $1 \leq i < j \leq 4$ modulo permutations of the index set $(1, 2, 3, 4)$. These 6 numbers are subject to 12 triangle inequalities; that is,

$$\ell_{i,j} + \ell_{j,k} \geq \ell_{i,k}$$

holds for all i, j and k , where we assume that $\ell_{j,i} = \ell_{i,j}$ and $\ell_{i,i} = 0$.

The space \mathcal{M}_4 comes with topology. It can be defined as a quotient of the cone in \mathbb{R}^6 by permutations of the 4-points of the space.

Consider the subset $\mathcal{E}_4 \subset \mathcal{M}_4$ of all isometry classes of 4-point metric spaces that admit isometric embeddings into Euclidean space.

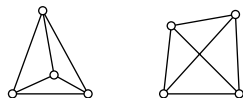


2.9. Advanced exercise. *The complement $\mathcal{M}_4 \setminus \mathcal{E}_4$ has two connected components.*

Let us denote one of the components by \mathcal{P}_4 and the other by \mathcal{N}_4 . Here \mathcal{P} and \mathcal{N} stand for positive and negative curvature because spheres have no quadruples of type \mathcal{N}_4 and Lobachevsky space has no quadruples of type \mathcal{P}_4 .

A metric space that has no quadruples of points of type \mathcal{P}_4 or \mathcal{N}_4 respectively is called CAT(0) and CBB(0).

Let us describe the subdivision into \mathcal{P}_4 , \mathcal{E}_4 , and \mathcal{N}_4 intuitively. Imagine that you move out of \mathcal{E}_4 — your path is a one-parameter family of 4-point metric spaces. The last thing you see in \mathcal{E}_4 is one of the two plane configurations



shown on the diagram. If you see the left configuration then you move into \mathcal{N}_4 ; if it is the one on the right, then you move into \mathcal{P}_4 . More degenerate pictures can be avoided; for example, a triangle with a point on a side. From such a configuration one may move in \mathcal{N}_4 and \mathcal{P}_4 (as well as come back to \mathcal{E}_4).

Here is an exercise, solving which would force you to rebuild a considerable part of Alexandrov geometry. It might be helpful to spend some time thinking about this exercise before proceeding.

2.10. Advanced exercise. *Assume \mathcal{X} is a geodesic space, containing only quadruples of type \mathcal{E}_4 . Show that \mathcal{X} is isometric to a convex set in a Hilbert space.*

In the definition above, instead of Euclidean space one can take Lobachevsky space of curvature -1 . In this case, one obtains the definition of spaces with curvature bounded above or below by -1 (CAT(-1) or CBB(-1)).

To define spaces with curvature bounded above or below by 1 (CAT(1) or CBB(1)), one has to take the unit 3-sphere and specify that only the quadruples of points such that each of the four triangles has perimeter less than $2 \cdot \pi$ are checked.

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