

Exercises in
Orthodox Geometry

Edited by
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Instead of Introduction

I am collecting these problems for fun, but they might be used to improve the problem solving skills in geometry. Every problem has a short elegant solution — this gives a hint which was not available when it was solved for the first time.

How to read the book. Open at a random chapter, make sure you like the practice problem.

If yes try to solve a random problem in the chapter. A semisolution is given in the end of the chapter, but you expected to think before reading it, otherwise it might not help.

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Very special thanks for everyone who shared the problems with me.

Some problems are marked by \circ , $*$, $+$ or \sharp .

\circ — easy problem;

$*$ — the solution requires at least two ideas;

$+$ — the solution requires knowledge of a theorem;

\sharp — there are interesting solutions based on different ideas.

Chapter 1

Curves

Recall that a *curve* is a continuous map defined on real interval and a *closed curve* is a continuous map defined on a circle. If the map is injective then the curve is called *simple*.

In this chapter we consider only plane and spherical curves. We assume that the reader is familiar with related definitions including length of curve and its curvature. The necessary material is covered in a the first couple of lectures of a standard introduction to differential geometry, see [1, §26–27] or [2, Chapter 1].

We give a practice problem with a solution, after that you are on your own.

Spiral

The following problem states that if you drive on the plane and turn the steering wheel to the right all the time, then you will not be able to come back to the same place.

▣ Assume γ is a smooth regular plane curve with strictly monotonic curvature. Show that γ has no self-intersections.

Solution. Without loss of generality we may assume that the curve is parametrized by its length and its curvature decreases.

Let $z(t)$ be the center of osculating circle at $\gamma(t)$ and $r(t)$ is its radius. That is

$$z(t) = \gamma(t) + \frac{\ddot{\gamma}(t)}{|\ddot{\gamma}(t)|^2}, \quad r(t) = \frac{1}{|\ddot{\gamma}(t)|}.$$



Straightforward calculations show that

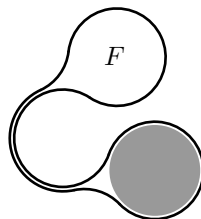
$$|\dot{z}(t)| \leq \dot{r}(t).$$

It follows that the osculating discs are nested; that is, $D_{t_1} \supset D_{t_0}$ for $t_1 > t_0$. Hence the result follows. \square

This problem gives a continuous analog of the Leibniz's test for alternating series. It was considered by Peter Tait in [3] and later rediscovered by Adolf Kneser in [4]; see also [5].

The moon in the puddle

\square A smooth closed simple plane curve with curvature less than 1 bounds a figure F . Prove that F contains a disc of radius 1.



A spring in a tin

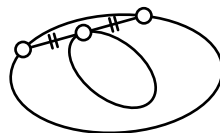
\square Let α be a closed smooth immersed curve inside a unit disc. Prove that the average absolute curvature of α is at least 1, with equality if and only if α is the unit circle possibly traversed more than once.

A curve in a sphere

\square Show that if a closed curve on the unit sphere intersects every equator then it has length at least 2π .

Oval in oval

\square Consider two closed smooth strictly convex planar curves, one inside the other. Show that there is a chord of the outer curve, which is tangent to the inner curve at its midpoint.



Capture a sphere in a knot*

The following problem states that one can not capture a sphere in a knot.

The precise formulation use the notion of smooth isotopy of knots; that is, one parameter of embeddings

$$f_t: \mathbb{S}^1 \rightarrow \mathbb{R}^3, \quad t \in [0, 1]$$

such that the map $[0, 1] \times \mathbb{S}^1 \rightarrow \mathbb{R}^3$ is smooth.

☞ Let B be the closed unit ball in \mathbb{R}^3 and $f: \mathbb{S}^1 \rightarrow \mathbb{R}^3 \setminus B$ be a knot. Show that there is a smooth isotopy

$$f_t: \mathbb{S}^1 \rightarrow \mathbb{R}^3 \setminus B, \quad t \in [0, 1],$$

such that $f_0 = f$, the length of f_t does not increase in t and $f_1(\mathbb{S}^1)$ can be separated from B by a plane.

Linked circles

☞ Suppose that two linked simple closed curves in \mathbb{R}^3 lie at a distance at least 1 from each other. Show that the length of each curve is at least $2 \cdot \pi$.

Surrounded area

☞ Let $\gamma_1, \gamma_2: \mathbb{S}^1 \rightarrow \mathbb{R}^2$ be two simple closed plane curves. Assume

$$|\gamma_1(v) - \gamma_1(w)| \leq |\gamma_2(v) - \gamma_2(w)|$$

for any $v, w \in \mathbb{S}^1$. Show that the area surrounded by γ_1 does not exceed the area surrounded by γ_2 .

Fat curve

☞ Construct a simple plane curve with positive Lebesgue measure.

Crooked circle

☞ Construct a bounded open disc in \mathbb{R}^2 such that its boundary contains no simple curve.

Rectifiable curve

In the following problem we use the notion of *Hausdorff measure* for the compact subsets in the plane. Fix a compact set $X \subset \mathbb{R}^2$ and $\alpha > 0$. Given $\delta > 0$ consider the value

$$h(\delta) = \inf \left\{ \sum_i (\text{diam } X_i)^\alpha \right\}$$

where the infimum is taken for all coverings of X by $\{X_i\}$ such that $\text{diam } X_i < \delta$ for each i .

Note that the function $\delta \mapsto h(\delta)$ does not decrease in δ . In particular, the limit h of $h(\delta)$ as $\delta \rightarrow 0$ is defined, possibly infinite. This value h is called α -dimensional Hausdorff measure of X .

▮ Assume X is a compact connected set in \mathbb{R}^2 with finite 1-dimensional Hausdorff measure. Show that X can be represented as the image of a rectifiable curve.

Typical convex functions

Recall that *G-delta set* is defined as a countable intersection of open sets. According to *Baire category theorem*, in a complete metric spaces, any intersection of countable collection of dense open set has to be dense.

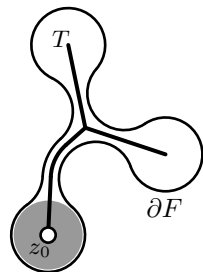
In particular, in a complete metric spaces, the intersection of a finite or countable collection of G-delta dense sets is also G-delta dense. The later means that G-delta dense sets contains *most* of the points of a complete metric space. This is the meaning of the word *most* used in the following problem.

▮ Consider the space of continuous convex functions defined on $[0, 1]$, equipped with the metric induced by sup norm.

Show that most of these functions have vanishing the second derivative at any point where it is defined.

Semisolutions

The moon in the puddle. Consider the *cut locus* T of F with respect to ∂F ; it is defined as the closure of the set of points $x \in F$ such that there are two or more points in ∂F which minimize distance to x .



Note that after a small perturbation of ∂F we may assume that T is a graph embedded in F with finite number of edges.

Note that T is a deformation retract of F . The retraction can be obtained by moving each point $y \in F \setminus T$ to T along the geodesic from the closest point to y on ∂F which pass through y .

In particular, T is a tree. Therefore T has at least two end vertices; Denote one of them by z .

Prove that the disc of radius 1 centered at z lies completely in F . □

The problem discussed by German Pestov and Vladimir Ionin in [6]. An other solution via curve shortening flow was given by Konstantin Pankrashkin in [7]. The statement still holds if the curve fails to be smooth at one point. A spherical version of the later statement was used by Dmitri Panov and me in [8].

The 3-dimensional analog of this statement does not hold. Namely, there is a smooth embedding $\mathbb{S}^2 \hookrightarrow \mathbb{R}^3$ with all the principle curvatures between -1 and 1 such that it does not surround a ball of radius 1 . Such example can be obtained by fattening a nontrivial contractible 2-complex in \mathbb{R}^3 [the Bing's house constructed in 9, will do the job]. Similar constructions were given by Vladimir Lagunov in [10].

A similar argument shows that for any point $p \in (\mathbb{S}^2, g)$ there is a minimizing geodesic $[pq]$ with conjugate ends. On the other hand, for (\mathbb{S}^3, g) this is not true. In fact, there are Riemannian metrics on \mathbb{S}^3 without minimizing geodesics with conjugate ends, yet more restrictive example is given in [11].

A spring in a tin. Let α be a closed curve in the unit disc; denote by ℓ its length.

Let us equip the plane with complex coordinates so that 0 is the center of the unit disc. We can assume that α equipped with ℓ -periodic parametrization by length.

Consider the curve $\beta(t) = t - \frac{\alpha(t)}{\dot{\alpha}(t)}$. Note that

$$\beta(t + \ell) = \beta(t) + \ell$$

for any t . In particular

$$\text{length}(\beta|_{[0, \ell]}) \geq |\beta(\ell) - \beta(0)| = \ell.$$

Note that

$$\begin{aligned} |\dot{\beta}(t)| &= \left| \frac{\alpha(t) \cdot \ddot{\alpha}(t)}{\dot{\alpha}(t)^2} \right| \leq \\ &\leq |\ddot{\alpha}(t)|. \end{aligned}$$

Since $|\ddot{\alpha}(t)|$ is the curvature of α at t , we get the result. \square

The statement was originally proved by István Fáry in [12]; number of different proofs are discussed by Serge Tabachnikov in [13], see also [19.5 in 14].

If instead of a disc, we have a region bounded by closed convex curve γ , then it is still true that the average curvature of α is at least as big as average curvature of γ . The proof was given by Jeffrey Lagarias and Thomas Richardson in [15], see also [16].

A curve in a sphere. We give two solutions, both by contradiction. Assume that α is a closed curve in \mathbb{S}^2 of length $2\cdot\ell$ which intersects each equator. Let us present two solutions.

A solution with the Crofton formula. Note that we can assume that α is a broken line.

Given a unit vector u denote by e_u the equator with pole at u . Let $k(u)$ the number of intersections of the α and e_u .

Note that for almost all $u \in \mathbb{S}^2$, the value $k(u)$ is even. Since each equator intersects α , we get $k(u) \geq 2$ for almost all u .

Then we get

$$\begin{aligned} 2\cdot\ell &= \frac{1}{4} \cdot \int_{\mathbb{S}^2} k(u) \cdot d_u \text{ area} \geq \\ &\geq \frac{1}{2} \cdot \text{area } \mathbb{S}^2 = \\ &= 2\cdot\pi. \end{aligned}$$

The first identity above is called *Crofton formula*. To prove this identity, consider a curve formed by on geodesic segment and then sum up the obtained identities for all segments in α . \square

A solution by symmetry. Let $\check{\alpha}$ be a sub-arc of α of length ℓ , with endpoints p and q . Let z be the midpoint of a minimizing geodesic $[pq]$ in \mathbb{S}^2 .

Let r be a point of intersection of α with the equator with pole at z . Without loss of generality we may assume that $r \in \check{\alpha}$.

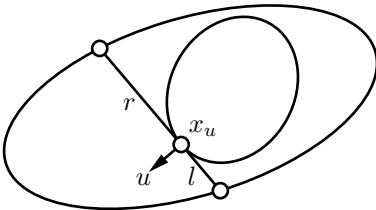
The arc $\check{\alpha}$ together with its reflection in z form a closed curve of length $2\cdot\ell$ that passes through r and its antipodal point r^* . Therefore

$$\ell = \text{length } \check{\alpha} \geq |r - r^*|_{\mathbb{S}^2} = \pi.$$

Here $|r - r^*|_{\mathbb{S}^2}$ denotes the angle metric in the sphere \mathbb{S}^2 . \square

The problem was suggested by Nikolai Nadirashvili.

Oval in oval. Show that the chord which minimizes (or maximizes) the ratio, in which it divides the bigger oval, solves the problem. \square



Alternative solution. Given a unit vector u , denote by x_u the point on the inner curve with outer normal vector u . Draw a chord of outer curve which is tangent to the inner curve at x_u ; denote by $r = r(u)$ and $l = l(u)$ the lengths

of this chord at the right and left from x_u .

Arguing by contradiction, assume $r(u) \neq l(u)$ for any $u \in \mathbb{S}^1$. Since the functions r and l are continuous, we can assume that

$$(*) \quad r(u) > l(u) \text{ for any } u \in \mathbb{S}^1.$$

Prove that each of the following two integrals

$$\frac{1}{2} \cdot \int_{\mathbb{S}^1} r^2(u) \cdot du \quad \text{and} \quad \frac{1}{2} \cdot \int_{\mathbb{S}^1} l^2(u) \cdot du$$

gives the area between the curves. In particular, the integrals are equal to each other. The latter contradicts (*). \square

This is a problem of Serge Tabachnikov [see 17]. A closely related, so called *equal tangents problem* is discussed by the same author in [18].

Capture a sphere in a knot. We can assume that the knot is given by a diagram on the sphere.

Fix a Möbius transformation $\mathbb{S}^2 \rightarrow \mathbb{S}^2$ which is not an isometry. Denote by u its conformal factor. Since the Möbius transformation preserves total area, we get

$$\frac{1}{\text{area } \mathbb{S}^2} \cdot \int_{\mathbb{S}^2} u^2 = 1.$$

Therefore,

$$\frac{1}{\text{area } \mathbb{S}^2} \cdot \int_{\mathbb{S}^2} u < 1.$$

It follows that after a suitable rotation of \mathbb{S}^2 , the length of the knot decreases.

The same way one gets a continuous one parameter family of Möbius transformations which moves the knot in a hemisphere and allows the ball to escape. \square

This is a problem of Zarathustra Brady, the given solution is based on the idea of David Eppstein [see 19].

Linked circles. Denote the linked circles by α and β .

Fix a point $x \in \alpha$. Note that one can find another point $x^* \in \alpha$ such that the interval $[xx^*]$ intersects β , say at the point z . Otherwise we can move each point of α along the line segment to x . This deformation of α will not cross β ; the latter contradicts that α and β are linked.

Consider the curve α^* which is the central projection of α from z onto the unit sphere around z ; clearly

$$\text{length } \alpha \geq \text{length } \alpha^*.$$

Note that α^* passes through two antipodal points of the sphere; therefore

$$\text{length } \alpha^* \geq 2 \cdot \pi.$$

Hence the result follows. \square

This is the simplest case of so called *Gehring's problem*. The solution above was given by Michael Edelstein and Binyamin Schwarz in [20]; later the same solution was rediscovered few times.

Surrounded area. Denote by C_1 and C_2 the compact regions bounded by γ_1 and γ_2 correspondingly.

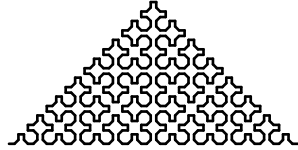
By Kirszbraun theorem, any short map $X \rightarrow \mathbb{R}^2$ defined on $X \subset \mathbb{R}^2$ can be extended to a short map on the whole \mathbb{R}^2 . In particular, there is a short map $f: \mathbb{R}^2 \rightarrow \mathbb{R}^2$ such that $f(\gamma_2(v)) = f(\gamma_1(v))$ for any $v \in \mathbb{S}^1$.

Note that $f(C_2) \supset C_1$. Whence the statement follows. \square

The Kirszbraun theorem appears in his thesis [see 21] and reproved later by Frederick Valentine in [22].

Fat curve. To solve the problem, you can modify your favorite space filling curve keeping its area nearly the same and removing the self-intersections.

It works for the *Sierpiński curve* which can be constructed as a limit of recursively defined sequence of curves; the 8th iteration is on the diagram. \square

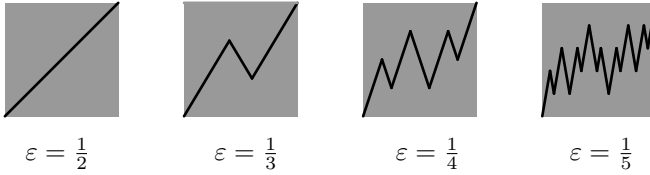


The existence of such curves was observed by William Osgood in [23].

Crooked circle. A continuous function $f: [0, 1] \rightarrow [0, 1]$ will be called ε -crooked if $f(0) = 0$, $f(1) = 1$ and for any segment $[a, b] \subset [0, 1]$ one can choose $a \leq x \leq y \leq b$ such that

$$|f(y) - f(a)| \leq \varepsilon \quad \text{and} \quad |f(x) - f(b)| \leq \varepsilon.$$

A sequence of $\frac{1}{n}$ -crooked maps can be constructed recursively. Guess the construction from the diagram.



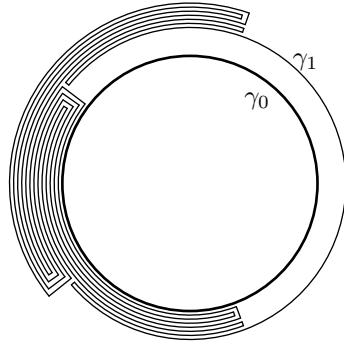
Start with the unit circle, $\gamma_0(t) = (\cos \frac{t}{2\pi}, \sin \frac{t}{2\pi})$. Construct recursively a sequence of simple closed curves $\gamma_n: [0, 1] \rightarrow \mathbb{R}^2$. Such that γ_{n+1} runs outside of the disc bounded by γ_n and

$$|\gamma_{n+1}(t) - \gamma_n \circ f_n(t)| < \varepsilon_n,$$

for some ε_n -crooked function $f_n: [0, 1] \rightarrow [0, 1]$.

On the diagram you see an attempt to draw the first iteration.

Denote by D the union of all discs bounded by γ_n . Show that D is homeomorphic to an open disc and for the right choice of the ε_n the set D is bounded and its boundary contains no simple curves. \square



The proof repeats the construction of pseudo-arc given by Bronisław Knaster in [24]. Let us list a few problems which can be solved the same way.

- ◇ Construct three disjoint non-empty open sets in \mathbb{R} which have the same boundary.
- ◇ Construct three open discs in \mathbb{R}^2 which have the same boundary. (This example are called *lakes of Wada*; it is described by Kunizō Yoneyama in [25].)
- ◇ Construct a Cantor set in \mathbb{R}^3 with non simply connected complement. (This example was is called *Antoine's necklace*; it is constructed in [26].)
- ◇ Construct an open set in \mathbb{R}^3 with fundamental group isomorphic to the additive group of rational numbers.

For more advanced examples check Whitehead manifold, *Dogbone space*, *Casson handle*; see also the problem “Conic neighborhood” on page 86.

Rectifiable curve. The 1-dimensional Hausdorff measure will be denoted as \mathcal{H}_1 .

Set $L = \mathcal{H}_1(K)$. Without loss of generality, we may assume that K has diameter 1.

Assume that $0 < \varepsilon < \frac{1}{2}$. Prove that

$$(*) \quad \mathcal{H}_1(B(x, \varepsilon) \cap K) \geq \varepsilon$$

for any $x \in K$.

Let x_1, \dots, x_n be a maximal set of points in K such that

$$|x_i - x_j| \geq \varepsilon$$

for all $i \neq j$. From $(*)$ we have $n \leq 2 \cdot L / \varepsilon$.

Construct a curve γ_ε such that (1) γ_ε is passing through all x_i , (2) $\text{length } \gamma_\varepsilon \leq 10 \cdot L$ and (3) γ_ε lies in ε -neighborhood of K . We can assume that γ_ε is parametrized by length.

The needed curve can be obtained by passing to a partial limit of γ_ε as $\varepsilon \rightarrow 0$. \square

This problem was given by Kenneth Falconer in his book [Exercise 3.5 in 27].

Typical convex functions. Denote by \mathfrak{F} the space of convex all functions defined on $[0, 1]$ with the sup-norm. Note that \mathfrak{F} is a complete metric space.

Prove that if a function $f \in \mathfrak{F}$ has nonzero derivative at some point then there is $\varepsilon > 0$ such that

$$|f - g| > \frac{\varepsilon}{n^{23}}$$

if $g \in \mathfrak{F}$ can be presented as a maximum of n linear functions.

Note that there is a countable set of piecewise linear convex g_1, g_2, \dots functions which is everywhere dense in \mathfrak{F} . Denote by n_i the number of linear intervals of g_i . For any positive integer k , consider the set $\Omega_k \subset \mathfrak{F}$ defined as

$$\Omega_k = \left\{ |f - g_i| < \frac{1}{k \cdot n_i^{23}} \mid \text{for some } i \right\}.$$

From above we get that if the second derivative of f does not vanishing at some point then $f \notin \Omega_k$ for large k .

Note that Ω_k is open and everywhere dense in \mathfrak{F} . Therefore

$$\Omega = \bigcap_k \Omega_k$$

is a G-delta dense set. Hence the statement follows. \square

This problem states that typical convex functions is very far from what we used to work with.

This is a typical answer for such question — typically we do not see the typical objects. For example, according to the result of Bernd Kirchheim, Emanuele Spadaro and László Székelyhidi proved in [28] a typical 1-Lipschitz maps from the plane to itself preserves the length of all curves. The same way one could show that the typical open discs in the plane contain no simple curves in their boundary, although the construction of one such is not trivial, see “Crooked circle” above.

More similar problems are surveyed by Tudor Zamfirescu in [29].

Chapter 2

Surfaces

In this chapter we consider mostly *smooth surfaces* in the Euclidean space. Once we consider an *abstract surfaces* that is two-dimensional Riemannian manifold.

We assume that the reader is familiar with related definitions including intrinsic metric, geodesics, convex and saddle surfaces, normal, principle and Gauss curvatures. A typical introductory course in differential geometry should cover all necessary background material, say [1, §28–29] or [2].

Convex hat

▣ Let Σ be a smooth closed convex surface in \mathbb{R}^3 and Π be a plane which cuts from Σ a disc Δ . Assume that the reflection of Δ in Π lies inside Σ . Show that Δ is convex in the intrinsic metric of Σ ; that is, if the ends of a minimizing geodesic in Σ lie in Δ , then whole geodesic lies in Δ .

Solution. Let γ be a minimizing geodesic with the ends in Δ .

Assume $\gamma \setminus \Delta \neq \emptyset$. Denote by $\hat{\gamma}$ the curve formed by $\gamma \cap \Delta$ and the reflection on $\gamma \setminus \Delta$ in Π . Note

$$\text{length } \hat{\gamma} = \text{length } \gamma$$

and $\hat{\gamma}$ runs partly inside and partly outside of the surface, but does not get inside of Σ .

Denote by $\bar{\gamma}$ the closest point projection of $\hat{\gamma}$ on Σ . The curve $\bar{\gamma}$ lies in Σ has the same ends as γ .

It remains to note that

$$\text{length } \bar{\gamma} < \text{length } \gamma;$$

the latter leads to a contradiction. \square

Unbended geodesic

\boxtimes Let Σ be a smooth closed convex surface in \mathbb{R}^3 and $\gamma: [0, \ell] \rightarrow \Sigma$ be a unit speed minimizing geodesic in Σ . Set $p = \gamma(0)$, $q = \gamma(\ell)$ and

$$p_t = \gamma(t) - t \cdot \dot{\gamma}(t),$$

where $\dot{\gamma}(t)$ denotes the velocity vector of γ at t .

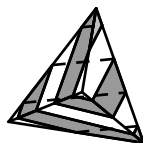
Show that for any $t \in (0, \ell)$, one cannot see q from p_t ; that is, the line segment $[p_t q]$ intersects Σ at a point distinct from q .

Corkscrew geodesic

\boxtimes Given a line ℓ in \mathbb{R}^3 construct a closed convex body K with a minimizing geodesic $\sigma: [a, b] \rightarrow \partial K$ in the surface of K which rotates 1000 times around ℓ ; that is, if $\varphi(t)$ is a continuous azimuth-function of $\sigma(t)$ in the cylindrical coordinates with axis at ℓ , then $|\varphi(b) - \varphi(a)| = 2000 \cdot \pi$.

Long geodesic

\boxtimes Assume that the surface of convex body B in \mathbb{R}^3 admits an arbitrary long closed simple geodesic. Show that B is a tetrahedron with equal opposite sides.



Geodesics for birds

Let $\gamma: [a, b] \rightarrow \mathbb{R}^m$ be a curve. The *total curvature* of γ is defined as supremum of sum of external angles for broken lines inscribed in γ . Namely,

$$\sup \left\{ \sum_{i=1}^{n-1} \alpha_i \mid a = t_0 < t_1 < \cdots < t_n = b \right\},$$

where $\alpha_i = \pi - \angle[\gamma(t_i)_{\gamma(t_{i+1})}]$.

If γ is smooth and parametrized by the arc length, then its total curvature equals to

$$\int_a^b |\ddot{\gamma}(t)| \cdot dt.$$

The *geodesics* in the following problem are defined as the curves locally minimizing the length.

▮ Let $f: \mathbb{R}^2 \rightarrow \mathbb{R}$ be a ℓ -Lipschitz function. Let $W \subset \mathbb{R}^3$ be the epigraph of f ; that is,

$$W = \{ (x, y, z) \in \mathbb{R}^3 \mid z \geq f(x, y) \}.$$

Equip W with the induced intrinsic metric.

Show that any geodesic in W has total curvature at most $2 \cdot \ell$.

Simple geodesic

▮ Let Σ be a complete unbounded convex surface in \mathbb{R}^3 . Show that there is a two-sided infinite geodesic in Σ with no self-intersections.

Immersed surface

▮ Let Σ be an immersed surface in \mathbb{R}^3 with strictly positive Gauss curvature and nonempty boundary $\partial\Sigma$. Assume $\partial\Sigma$ lies in a plane Π and whole Σ lies on one side from Π . Prove that Σ is an embedded disc.

Periodic asymptote

▮ Let Σ be a closed smooth surface with non-positive curvature and γ be a geodesic in Σ . Assume that γ is not periodic and the curvature of Σ vanish at every point of γ . Show that γ does not have a periodic asymptote; that is, there is no periodic geodesic δ such that the distance from $\gamma(t)$ to δ converges to 0 as $t \rightarrow \infty$.

Asymptotic line

Recall that *asymptotic line* on the smooth surface $\Sigma \subset \mathbb{R}^3$ is a curve always tangent to an *asymptotic direction* of Σ ; that is, the direction in which the normal curvature of Σ is zero.

We say that a smooth surface is *saddle* at point p if its principle curvatures at this point have opposite signs.

▮ Let $\Sigma \subset \mathbb{R}^3$ be the graph $z = f(x, y)$ of smooth function f and γ be a closed smooth asymptotic line in Σ . Assume Σ is strictly saddle in a neighborhood of γ . Prove that the projection of γ to the xy -plane cannot be star-shaped.

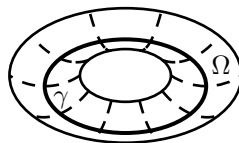
A minimal surface

Recall that a smooth surface in \mathbb{R}^3 is called *minimal* if its mean curvature vanish at all points. The *mean curvature* is defined as the sum of the principle curvatures at the point.

▮ Let Σ be a minimal surface in \mathbb{R}^3 which has boundary on a unit sphere. Assume Σ passes through the center of the sphere. Show that the area of Σ is at least π .

Round gutter*

A round gutter is the surface shown on the picture.



Formally: consider torus T ; that is, a surface generated by revolving a circle in \mathbb{R}^3 about an axis coplanar with the circle. Let $\gamma \subset T$ be one of the circles in T which locally separates positive and negative curvature on T ; a plane containing γ is tangent to T at all points of γ . Let Ω be a neighborhood of γ in T . The surface Ω will be called *round gutter* and the circle γ will be called its *main latitude*.

▮ Let $\Omega \subset \mathbb{R}^3$ is a round gutter with main latitude γ . Assume $\iota: \Omega \rightarrow \mathbb{R}^3$ is a smooth length-preserving embedding which is sufficiently close to the identity. Show that γ and $\iota(\gamma)$ are congruent; that is, there is a motion of \mathbb{R}^3 which sends γ to $\iota(\gamma)$

Non-contractible geodesics

▮ Give an example of a non-flat metric on the 2-torus such that it has no contractible geodesics.

The last problem of Poincaré*

▮ Let $f: \mathbb{C} \rightarrow \mathbb{C}$ be an area preserving homeomorphism such that

$$f(z) = \begin{cases} z - i & \text{if } \operatorname{Re}(z) \leq -1, \\ z + i & \text{if } \operatorname{Re}(z) \geq 1. \end{cases}$$

and $f(z + i) = f(z) + i$ for any $z \in \mathbb{C}$.

Show that f has a fixed point.

Two discs

☞ Let Σ_1 and Σ_2 be two smoothly embedded open discs in \mathbb{R}^3 which have a common closed smooth curve γ . Show that there is a pair of points $p_1 \in \Sigma_1$ and $p_2 \in \Sigma_2$ with parallel tangent planes.

Semisolutions

Unbended geodesic. Let W be the closed unbounded set formed by Σ and its exterior points.

Prove that for any $x \in \Sigma$ the distance $|x - p_t|$ is non-decreasing in t .

Use the latter statement, to prove the same for $|x - p_t|_W$, where $|x - p_t|_W$ stays for the intrinsic distance from x to p_t in W .

Prove that

$$|q - p|_W = |q - p|_\Sigma$$

for any $p, q \in \Sigma$.

Conclude that the distance $|q - p_t|_W = |q - p|_\Sigma$ for any t . It follows that the curve

$$\gamma_t(\tau) = \begin{cases} (\tau - t) \cdot \dot{\gamma}(\tau) & \text{if } \tau < t; \\ \gamma(\tau) & \text{if } \tau > t. \end{cases}$$

is a minimizing geodesic from p_t to q in the intrinsic metric of W .

If q is visible from p_t for some t then the line segment $[qp_t]$ intersects Σ only at q . From above, γ_t coincides with the line segment $[qp_t]$ which is impossible. \square

This observation was used by Anatoliy Milka to generalize Alexandrov's comparison theorem for convex surfaces [see 30].

Corkscrew geodesic. An example can be found among the surfaces of convex polyhedrons look like a vertical needle.

One can assume that the non-degenerate intersections of such polyhedron, say K , with horizontal planes are triangles with parallel sides.

On the surface of K there are three almost vertical broken lines, formed by the corresponding vertices of triangles. The polyhedron can be made in such a way that any minimizing geodesic from the top of K to its bottom has to cross these lines in the cyclic order at nearly each edge, and the number of edges can be made arbitrary large. (The projection of geodesic spirals around the origin.) \square

The construction is due to Imre Bárány, Krystyna Kuiperberg and Tudor Zamfirescu [see 31].

Long geodesic. Denote by a the area of the surface.

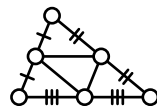
Cut the surface along a long closed simple geodesic γ . We get two discs with non-negative curvature and large perimeter, say ℓ . Note that the area of each disc is bounded above by a .

Choose one of the discs D and equip it with the intrinsic metric. Note that D is non-negatively curved in the sense of Alexandrov. Denote by p and q be the points in D which lie at the maximal distance from each other.

Fix $\varepsilon > 0$. Fix a geodesic $[pq]$ in D . Show that if ℓ is large enough in terms of ε , then the distance from any point in D to $[pq]$ is at most ε and the curvature of ε -neighborhood of p in D is at least $\pi - \varepsilon$.

By Gauss–Bonnet formula the total curvature of Σ is $4 \cdot \pi$. Since $\varepsilon > 0$ is arbitrary, we get that there are 4 point in Σ , each with curvature π and the remaining part of Σ is flat.

It remains to show that any surface with this property is isometric to the surface of a tetrahedron with equal opposite edges. To do this cut Σ along three geodesics which connect one singular point to the remaining three, develop the obtained flat surface on the plane and think (also look at the diagram).



□

The problem was suggested by Arseniy Akopyan.

Geodesics for birds. Consider a geodesic

$$t \mapsto (x(t), y(t), z(t))$$

in W ; assume it is defined in the interval $\mathbb{I} \subset \mathbb{R}$. Let us denote by φ the total curvature; it is a measure on \mathbb{I} . We need to estimate $\varphi(\mathbb{I})$.

Denote by $s = s(t)$ the natural parameter of the plane curve

$$t \mapsto (x(t), y(t)).$$

Prove that the function $f: s \mapsto z$ is concave.

Given a semi-open interval $\mathbb{J} = (a, b] \subset \mathbb{I}$, set $\mu(\mathbb{J}) = f^+(a) - f^+(b)$, where f^+ denotes right derivatives. The function μ extends to a measure which could be also written as

$$\mu = \frac{dz^2}{ds^2} \cdot ds.$$

if $\frac{dz^2}{ds^2}$ understood in the sense of distribution.

Note that $|\frac{dz}{ds}| \leq \ell$. In particular, $\mu(\mathbb{I}) \leq 2 \cdot \ell$.

Further note that $\varphi \leq \sqrt{1 + \ell^2} \cdot \mu$. In particular,

$$\varphi(\mathbb{I}) \leq 2 \cdot \ell \cdot \sqrt{1 + \ell^2}.$$

A straightforward improvement of these estimates gives

$$\varphi(\mathbb{I}) \leq 2 \cdot \ell.$$

This bound is optimal, check a both side infinite geodesic on the graph of

$$f(x, y) = -\ell \cdot \sqrt{x^2 + y^2}. \quad \square$$

The problem is due to David Berg [see 32]. The main observation (the concavity of the function $s \mapsto z$) is called *Lieberman's lemma*; it was used earlier to bound the total curvature of a geodesic on a convex surface [see 33].

Simple geodesic. Let γ be a two-sided infinite geodesic in Σ . The following is the key statement in the proof.

Claim. The geodesic γ contains at most one simple loop.

To prove the claim use the following observations.

- ◊ The integral curvature ω of Σ cannot exceed $2 \cdot \pi$.
- ◊ If φ is the angle at the base of a simple geodesic loop then the integral curvature surrounded by the loop equals to $\pi + \varphi$.

Once the claim is proved, note that, if a geodesic γ has a self-intersection, then it contains a simple loop. From above there is only one such loop; it cuts a disc from Σ and can go around it either clockwise or counterclockwise. This way we divide all the self-intersecting geodesics into two sets which we will call *clockwise* and *counterclockwise*.

Note that the geodesic $t \mapsto \gamma(t)$ is clockwise if and only if $t \mapsto \gamma(-t)$ is counterclockwise. The sets of clockwise and counterclockwise are open and the space of geodesics is connected. It follows that there are geodesics which are, neither clockwise, nor counterclockwise; by the definition, these geodesics have no self-intersections. \square

This idea is due to Victor Bangert [see Cor. 2 in 34].

Immersed surface. Let ℓ be a linear function which vanishes on Π and is positive in Σ .

Let z be a point of maximum of ℓ on Σ ; set $s_0 = \ell(z)$. Given $s < s_0$, denote by Σ_s the connected component of z in $\Sigma \cap \ell^{-1}([s, s_0])$. Note that for all s sufficiently close to s_0 we have

- ◊ Σ_s is an embedded disc;
- ◊ $\partial \Sigma_s$ is convex plane curve.

Applying open-closed argument, we get that the same holds for all $s \in [0, s_0)$.

Since Σ is connected, $\Sigma_0 = \Sigma$. Hence the result follows. \square

This problem is discussed in the lectures of Mikhael Gromov [see §₂¹ in 35].

Periodic asymptote. Assume the contrary. Passing to a finite cover, we can assume that the asymptote has no self intersections. In this case the restriction $\gamma|_{[a, \infty)}$ has no self-intersections, if a is large large enough.

Cut Σ along $\gamma([a, \infty))$ and then cut from the obtained surface an infinite triangle Δ . The triangle Δ should have two sides formed by both sides of cuts along γ ; let us denote these sides of Δ by γ_- and γ_+ . Note that

$$(*) \quad \text{area } \Delta < \text{area } \Sigma < \infty$$

and both sides γ_{\pm} form infinite minimizing geodesics in Δ .

Consider the Buseman function f for γ_+ ; denote by $\ell(t)$ the length of the level curve $f^{-1}(t)$. Let $-\kappa(t)$ be the total curvature of the suplevel set $f^{-1}([t, \infty))$. Note that for all large t we have

$$\ell'(t) = \kappa(t) \quad \text{and} \quad \kappa'(t) \leq C \cdot \ell(t)^2,$$

where C is a fixed constant. The latter implies that there is $\varepsilon > 0$ such that

$$\ell(t) \geq \frac{\varepsilon}{t - a}$$

for any large t . In particular,

$$\int_a^{\infty} \ell(t) = \infty.$$

By the coarea formula we get

$$\text{area } \Delta = \infty;$$

the latter contradicts (*). □

I've learned the problem from Dmitri Burago and Sergei Ivanov, it is originated from a discussion with Keith Burns, Michael Brin and Yakov Pesin.

Asymptotic line. Arguing by contradiction, assume that the projection $\bar{\gamma}$ of γ on xy -plane is star shaped with respect to the origin.

Consider the function

$$h(t) = (d_{\bar{\gamma}(t)} f)(\gamma(t)).$$

Prove that $h'(t) \neq 0$. In particular $h(t)$ is a strictly monotonic function of \mathbb{S}^1 , a contradiction. □

The problem is discussed by Dmitri Panov in [36].

A minimal surface. Without loss of generality we may assume that the sphere is centered at $0 \in \mathbb{R}^3$.

Consider the restriction h of the function $x \mapsto |x|^2$ to the surface Σ . Prove that $\Delta_\Sigma h \leq 4$ and apply the divergence theorem for $\nabla_\Sigma h$. It follows that the function

$$f: r \mapsto \frac{\text{area}(\Sigma \cap B(0, r))}{r^2}$$

is non-decreasing in the interval $(0, 1)$. Hence the result follows. \square

We described a partial case of so called *monotonicity formula*.

The same argument shows that if 0 is a double point of Σ then $\text{area } \Sigma \geq 2 \cdot \pi$. This observation was used in the proof that the minimal disc bounded by a simple closed curve with total curvature $\leq 4 \cdot \pi$ is necessarily embedded. The proof was given by Tobias Ekholm, Brian White and Daniel Wienholtz in [37]; an amusing simplification and generalization was obtained by Stephan Stadler. This result also implies the result of John Milnor that any embedded circle of total curvature at most $4 \cdot \pi$ is unknot [see 38].

Note that if we assume in addition that the surface is a disc, then the statement holds for any saddle surface. Indeed, denote by S_r the sphere of radius r concentrated with the unit sphere. Then according to the problem “A curve in a sphere” [page 6],

$$\text{length}(\Sigma \cap S_r) \geq 2 \cdot \pi \cdot r.$$

Then the coarea formula leads to the solution.

On the other hand there are saddle surfaces homeomorphic to the cylinder that may have arbitrary small area in the ball.

If Σ does not pass through the center and we only know the distance, say r , from the center to Σ , then the optimal bound is expected to be $\pi \cdot (1 - r^2)$. This is known if Σ is homeomorphic to a disc. This is also known for the area minimizing surfaces; an analogous statement holds in all dimensions and codimensions. These results were proved by Herbert Alexander, David Hoffman and Robert Osserman [see 39, 40].

Round gutter. Let K be the convex hull of $\Omega' = \iota(\Omega)$. Consider the boundary curve γ' of $\partial K \cap \Omega'$ in Ω' .

First note that the Gauss curvature of Ω' has to vanish at the points of γ' ; in other words, $\gamma' = \iota(\gamma)$. Indeed since γ' lies on convex part, the Gauss curvature at the points of γ' has to be non-negative. On the other hand γ' bounds a flat disc in ∂K ; therefore its integral

intrinsic curvature has to be $2\cdot\pi$. If the Gauss curvature is positive at some point of γ' , then total intrinsic curvature of γ' has to be $< 2\cdot\pi$, a contradiction.

Now prove that γ' is an asymptotic line. (Assume that the asymptotic direction goes transversely to $\gamma'(t)$ and conclude $\gamma(t) \notin \partial K$.)

Without loss of generality, we can assume that the length of γ is $2\cdot\pi$ and its intrinsic curvature is $\equiv 1$. Therefore, as the space curve, γ' has to be a curve with constant curvature 1 and it should be closed. Any such curve is congruent to a flat circle. \square

It is not known if Ω' is congruent to Ω .

The solution presented above is based on my answer to the question of Joseph O'Rourke [see 41]. Here are some related statements.

- ◊ A half-torus is second order rigid; this was proved by Eduard Rembs in [42], see also [43, p. 135].
- ◊ Any second order rigid surface does not admit analytic deformation [proved by Nikolay Efimov, see 43, p. 121] and for the surfaces of revolution, the assumption of analyticity can be removed [proved by Idzhad Sabitov, see 44].

Non-contractible geodesics. Take a torus of revolution T . It has a family *meridians* — the family of circles which form closed geodesics.

Note that a geodesic on T is either a meridian or it intersects meridians transversally. No closed curve of these types can be contractible. \square

I know this problem from the book of Mikhael Gromov [see 45], where it is attributed to Y. Colin de Verdière. I am not aware of any solutions which do not admit a foliation by geodesics.

The last problem of Poincaré. Set

$$H_+ = \{ z \in \mathbb{C} \mid \operatorname{Re}(z) \geq 1 \},$$

$$H_- = \{ z \in \mathbb{C} \mid \operatorname{Re}(z) \leq -1 \}.$$

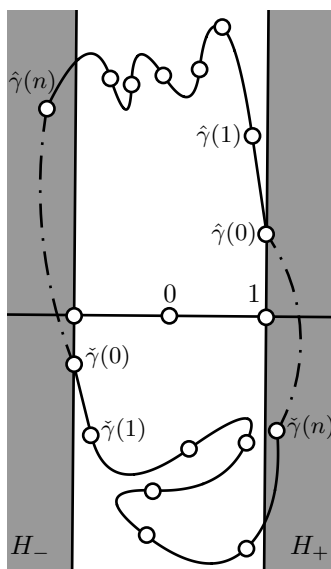
Assume f has no fixed points; in other words the image of the map

$$\varphi: z \mapsto f(z) - z$$

lies in $\mathbb{C}^* = \mathbb{C} \setminus \{0\}$.

Fix $\varepsilon > 0$ such that $|f(z) - z| > \varepsilon$ for any $z \in \mathbb{C}$. Note that the map

$$\check{f}: z \mapsto f(z) + \varepsilon$$



is area preserving and has no fixed points.

Prove that for some positive integer n , there is a curve

$$\tilde{\gamma}: [0, n] \rightarrow \mathbb{C}$$

which starts in H_- , ends in H_+ and $\tilde{f} \circ \tilde{\gamma}(t) = \tilde{\gamma}(t+1)$ for any $t \in [0, n-1]$.

Repeat the same construction for the function $\hat{f}(z) = f(z) - \varepsilon$ and obtain a curve $\hat{\gamma}: [0, n] \rightarrow \mathbb{C}$ starting in H_+ and ending in H_- .

Connect $\tilde{\gamma}(n)$ to $\hat{\gamma}(0)$ by a curve in H_+ and $\hat{\gamma}(n)$ to $\tilde{\gamma}(0)$ by a curve in H_- . Denote by σ the obtained loop.

Prove that

- ◊ The loop $\varphi \circ \sigma$ has to be null-homotopic in \mathbb{C}^* .
- ◊ The loop $\varphi \circ \sigma$ is a generator of $\pi_1 \mathbb{C}^*$.

These two statements contradict each other. □

The problem was proposed by Henri Poincaré [see 46] and solved by George Birkhoff in [47].

Two discs. Choose a continuous map $h: \Sigma_1 \rightarrow \Sigma_2$ which is identical on γ . Let us prove that for some $p_1 \in \Sigma_1$ and $p_2 = h(p_1) \in \Sigma_2$ the tangent plane $T_{p_1} \Sigma_1$ is parallel to the tangent plane $T_{p_2} \Sigma_2$; this is stronger than required.

Arguing by contradiction, assume that such point does not exist. Then for each $p \in \Sigma_1$ there is unique line $\ell_p \ni p$ which is parallel to each of the the tangent planes $T_p \Sigma_1$ and $T_{h(p)} \Sigma_2$.

Note that the lines ℓ_p form a tangent line distribution over Σ_1 and ℓ_p is tangent to γ at any $p \in \gamma$.

Let D be the disc in Σ_1 bounded by γ . Consider the doubling of D in γ ; it is diffeomorphic to \mathbb{S}^2 . The line distribution ℓ lifts to a line distribution on the doubling; the latter contradicts the hairy ball theorem. □

This proof was suggested nearly simultaneously by Steven Sivek and Damiano Testa [see 48].

Note that the same proof works in case Σ_i are oriented open surfaces such that γ cuts a compact domain in each Σ_i .

There are examples of three disks Σ_1 , Σ_2 and Σ_3 with a common closed curve γ such that there no triple of points $p_i \in \Sigma_i$ with parallel tangent planes. Such examples can be found among ruled surfaces [see 49].

Chapter 3

Comparison geometry

In this chapter we consider Riemannian manifolds with curvature bounds.

This chapter is the very demanding; we assume that the reader is familiar with the main definitions in the subject, including Jacobi fields, Shape operator and second fundamental form, equations of Riccati and Jacobi, comparison theorems and Morse theory. The classical book [50] by Cheeger and Ebin covers all the necessary material.

Geodesic immersion^{*}

☞ Let M be a simply connected positively curved Riemannian manifold and $\iota: N \looparrowright M$ be a totally geodesic immersion. Assume that

$$\dim N > \frac{1}{2} \cdot \dim M.$$

Prove that ι is an embedding.

Semisolution. Set $n = \dim N$, $m = \dim M$.

Fix a smooth increasing strictly concave function φ . Consider the function $f = \varphi \circ \text{dist}_N$.

Note that if f is smooth at some point $x \in M$ then $\text{Hess}_x f$, the Hessian of f at x , has at least $n + 1$ negative eigenvalues.

Moreover, at any point $x \notin \iota(N)$ the same holds in the barrier sense. That is, there is a smooth function h defined on M such that $h(x) = f(x)$, $h(y) \geq f(y)$ for any y and $\text{Hess}_x h$ has at least $n + 1$ negative eigenvalues.

Use that $m < 2 \cdot n$ and the described property to prove the following analog of Morse lemma for f .

Claim. *Given $x \notin \iota(N)$ there is a neighborhood $U \ni x$ such that the set*

$$U_- = \{ z \in U \mid f(z) < f(x) \}$$

is simply connected.

Since M is simply connected, any closed curve in $\iota(N)$ can be contracted by a disc, say $s_0: \mathbb{D} \rightarrow M$.

Applying the claim, one can construct an f -decreasing homotopy starting at s_0 . That is, there is an homotopy $s_t: \mathbb{D} \rightarrow M$, $t \in [0, 1]$ such that $s_t(\partial\mathbb{D}) \subset \iota(N)$ for any t and $s_1(\mathbb{D}) \subset \iota(N)$. It follows that $\iota(N)$ is simply connected.

Finally note that if $\iota: N \rightarrow M$ has a self-intersection, then the image $\iota(N)$ is not simply connected. Hence the result follows. \square

The statement was proved by Fuquan Fang, Sérgio Mendonça and Xiaochun Rong in [51]. The main idea was discovered by Burkhard Wilking [see 52].

Geodesic hypersurface

\square *Prove that if a compact connected positively curved manifold M admits a totally geodesic embedded hypersurface, then M or its double cover is homeomorphic to the sphere.*

If convex, then embedded

\square *Let M be a complete simply connected Riemannian manifold with non-positive curvature and dimension at least 3. Prove that any immersed locally convex compact hypersurface in M is embedded.*

Immersed ball*

\square *Prove that any immersed locally convex hypersurface $\iota: \Sigma \looparrowright M$ in a compact positively curved manifold M of dimension $m \geq 3$, is the boundary of an immersed ball. That is, there is an immersion of a closed ball $f: \bar{B}^m \looparrowright M$ and a diffeomorphism $h: \Sigma \rightarrow \partial\bar{B}^m$ such that $\iota = f \circ h$.*

Minimal surface in the sphere

A smooth n -dimensional surface Σ in an m -dimensional Riemannian manifold M is called minimal if it locally minimized the n -dimensional

area; that is, sufficiently small regions of Σ do not admit area decreasing deformations with fixed boundary.

The minimal surfaces can be also defined via mean curvature vector as follows. Let $T = T\Sigma$ and $N = N\Sigma$ correspondingly tangent and normal bundle. Let s denotes the second fundamental form of Σ ; it is a quadratic form on T with values in N . Let e_i is an orthonormal basis for T_x , set

$$H_x = \sum_i s(e_i, e_i) \in N_x;$$

it is the mean curvature vector at $x \in \Sigma$. We say that Σ is *minimal* if $H \equiv 0$.

☞ Let Σ be a closed n -dimensional minimal surface in \mathbb{S}^m . Prove that $\text{vol}_n \Sigma \geq \text{vol}_n \mathbb{S}^n$.

Hypercurve

The Riemannian curvature tensor R can be viewed as an operator \mathbf{R} on the space of tangent bi-vectors $\bigwedge^2 T$; it is uniquely defined by identity

$$\langle \mathbf{R}(X \wedge Y), V \wedge W \rangle = \langle R(X, Y)V, W \rangle,$$

The operator $\mathbf{R}: \bigwedge^2 T \rightarrow \bigwedge^2 T$ is called *curvature operator* and it is said to be *positive definite* if $\langle \mathbf{R}(\varphi), \varphi \rangle > 0$ for all non zero bi-vector $\varphi \in \bigwedge^2 T$.

☞ Let $M^m \hookrightarrow \mathbb{R}^{m+2}$ be a closed smooth m -dimensional submanifold and let g be the induced Riemannian metric on M^m . Assume that sectional curvature of g is positive. Prove that the curvature operator of g is positive definite.

The second fundamental form for manifolds of arbitrary codimension which we are about to describe might help to solve this problem.

Assume M is a smooth submanifold in \mathbb{R}^m . Given a point $p \in M$ denote by T_p and $N_p = T_p^\perp$ the tangent and normal spaces of M at p . The *second fundamental form* of M at p is defined as

$$s(X, Y) = (\nabla_X Y)^\perp,$$

where $(\nabla_X Y)^\perp$ denotes the orthogonal projection of covariant derivative $\nabla_X Y$ onto the normal bundle.

The curvature tensor of M can be found from the second fundamental form using the following formula

$$\langle R(X, Y)Y, X \rangle = \langle s(X, X), s(Y, Y) \rangle - \langle s(X, Y), s(X, Y) \rangle,$$

which is direct generalization of the formula for Gauss curvature of surface.

Horosphere

We say that a Riemannian manifold has negatively pinched sectional curvature, if its sectional curvature at any point in any sectional direction lies in $[-a^2, -b^2]$, for fixed constants $a > b > 0$.

Let M be a complete Riemannian manifold and γ is a ray in M ; that is, $\gamma: [0, \infty) \rightarrow M$ is a minimizing unit-speed geodesic.

The *Busemann function* $b_\gamma: M \rightarrow \mathbb{R}$ is defined by

$$b_\gamma(p) = \lim_{t \rightarrow \infty} (|p - \gamma(t)|_X - t).$$

From the triangle inequality, the expression under the limit is non-increasing in t ; therefore the limit above is defined for any p .

A *horosphere* in M is defined as a level set of a Busemann function in M .

We say that a complete Riemannian manifold M has *polynomial volume growth* if for some (and therefore any) $p \in M$, we have

$$\text{vol } B(p, r)_M \leq C \cdot (r^k + 1),$$

where $B(p, r)_M$ is the ball in M and C, k are real constants.

☐ *Let M be a complete simply connected manifold with negatively pinched sectional curvature. And let $\Sigma \subset M$ be an horosphere in M . Prove that Σ with the induced intrinsic metric has polynomial volume growth.*

Minimal spheres

Recall that two subsets A and B in a metric space X are called *equidistant* if the distance function $\text{dist}_A: X \rightarrow \mathbb{R}$ is constant on B and dist_B is constant on A .

The minimal surfaces are defined on page 28.

☐ *Show that a 4-dimensional compact positively curved Riemannian manifold cannot contain infinite number of mutually equidistant minimal 2-spheres.*

Positive curvature and symmetry⁺

☐ *Assume \mathbb{S}^1 acts isometrically on a 4-dimensional positively curved closed Riemannian manifold. Show that the action has at most 3 isolated fixed points.*

Let us give some background material which can help to solve the problem.

Let X and Y be metric spaces. An onto map $f: X \rightarrow Y$ is called *submetry* if it is short and for any $x \in X$ and $y \in Y$ there is $x' \in X$ such that

$$f(x') = y \quad \text{and} \quad |x - x'|_X = |f(x) - y|_Y.$$

Here is a general statement required in the proof.

- ◊ If $f: X \rightarrow Y$ is a submetry and X is an Alexandrov space with curvature $\geq \kappa$, then Y is also an Alexandrov space with curvature $\geq \kappa$.

Note that if G is a compact subgroup of isometries of a metric space X , then the quotient map $X \rightarrow X/G$ is a submetry, assuming that the orbit space X/G equipped with the Hausdorff metric on the orbits.

Complete Riemannian manifold with sectional curvature $\geq \kappa$ are Alexandrov spaces.

The following statement follows from the one above and it can be used directly in the solution.

- ◊ If (M, g) is a Riemannian manifold with sectional curvature ≥ 1 which admits a continuous isometric action of \mathbb{S}^1 , then $(M, g)/\mathbb{S}^1$ is an Alexandrov space with curvature ≥ 1 .

For more on Alexandrov Geometry, see [53]. □

Energy minimizer

Let F be a smooth map from a closed Riemannian manifold M to a Riemannian manifold N . Then energy functional of F is defined as

$$E(F) = \int_M |d_x F|^2 \cdot d_x \text{vol}_M.$$

If $(a_{i,j})$ denote the components of the differential $d_x F$ written in the orthonormal bases of the tangent spaces $T_x M$ and $T_{F(x)} N$, then

$$|d_x F|^2 = \sum_{i,j} a_{i,j}^2.$$

☞ Show that the identity map on \mathbb{RP}^m is energy minimizing in its homotopy class. Here we assume that \mathbb{RP}^m is equipped with canonical metric.

Curvature vs. injectivity radius⁺

☞ Let (M, g) be a closed Riemannian m -dimensional manifold. Assume average of sectional curvatures of (M, g) is 1. Show that the injectivity radius of (M, g) is at most π .

A solution use a corollary of Liouville's theorem which states that geodesic flow on the tangent bundle to a Riemannian manifold preserves the volume form.

Almost flat manifold

Nil-manifolds form the minimal class of manifolds which includes a point, and has the following property: the total space of any principle S^1 -bundle over a nil-manifold is a nil-manifold.

Th nil-manifold can be also defined as the quotients of a connected nilpotent Lie group by a lattice.

A compact Riemannian manifold M is called ε -flat if its sectional curvature at all points in all directions lie in the interval $[-\varepsilon, \varepsilon]$.

The main theorem of Gromov in [54], states that for any positive integer n there is $\varepsilon > 0$ such that any ε -flat compact n -dimensional manifold with diameter at most 1 admits a finite cover by a nil-manifold. A more detailed proof can be found in [55] and a more precise statement can be found in [56].

▮ Given $\varepsilon > 0$ construct a compact Riemannian manifold M of sufficiently large dimension which admits a Riemannian metric with diameter ≤ 1 and sectional curvature $|K| < \varepsilon$, but does not admit a finite covering by a nil-manifold.

Approximation of quotient

▮ Let (M, g) be a compact Riemannian manifold and G is a compact Lie group acting by isometries on (M, g) . Construct a sequence of metrics g_n on a fixed manifold N such that (N, g_n) converges to the quotient space $(M, g)/G$ in the sense of Gromov-Hausdorff.

Polar points[#]

▮ Let M be a compact Riemannian manifold with sectional curvature ≥ 1 and $\dim M \geq 2$. Prove that for any point $p \in M$ there is a point $p^* \in M$ such that

$$|p - x|_M + |x - p^*|_M \leq \pi$$

for any $x \in M$.

Isometric section*

▮ Let M and W be compact Riemannian manifolds, $\dim W > \dim M$ and $s: W \rightarrow M$ be a Riemannian submersion. Assume that W has

positive sectional curvature. Show that s does not admit an isometric section; that is, there is no isometric embedding $\iota: M \hookrightarrow W$ such that $s \circ \iota(p) = p$ for any $p \in M$.

Warped product

Let (M, g) and (N, h) be Riemannian manifolds and f be a smooth positive function defined on M . Consider the product manifold $W = M \times N$. Given a tangent vector $X \in T_{(p,q)}W = T_pM \times T_qN$ denote by $X_M \in TM$ and $X_N \in TN$ its projections. Let us equip W with the Riemannian metric defined as

$$s(X, Y) = g(X_M, Y_M) + f^2 \cdot h(X_N, Y_N).$$

The obtained Riemannian manifold (W, s) is called *warped product* of M and N with respect to $f: M \rightarrow \mathbb{R}$; it can be written as $(W, g) = (N, h) \times_f (M, g)$.

▮ Assume M is an oriented 3-dimensional Riemannian manifold with positive scalar curvature and $\Sigma \subset M$ is an oriented smooth hypersurface which is area minimizing in its homology class.

Show that there is a positive smooth function $f: \Sigma \rightarrow \mathbb{R}$ such that the warped product $\mathbb{S}^1 \times_f \Sigma$ has positive scalar curvature; here Σ is equipped with the Riemannian metric induced from M .

No approximation[‡]

▮ Prove that if $p \neq 2$, then \mathbb{R}^m equipped with the metric induced by the ℓ^p -norm cannot be a Gromov–Hausdorff limit of m -dimensional Riemannian manifolds (M_n, g_n) with $\text{Ric}_{g_n} \geq C$ for some fixed constant $C \in \mathbb{R}$.

Area of spheres

▮ Let M be a complete non-compact Riemannian manifold with non-negative Ricci curvature and $p \in M$. Then there is $\varepsilon > 0$ such that

$$\text{area}[\partial B(p, r)] > \varepsilon$$

for all sufficiently large r .

Curvature hollow

▮ Construct a Riemannian metric on \mathbb{R}^3 which is Euclidean outside of an open bounded set Ω and with negative scalar curvature in Ω .

Flat coordinate planes

▮ Let g be a Riemannian metric on \mathbb{R}^3 , such that the coordinate planes $x = 0$, $y = 0$ and $z = 0$ are flat and totally geodesic. Assume the sectional curvature of g is either non-negative or non-positive. Show that in both cases g is flat.

Two-convexity[‡]

An open subset V with smooth boundary in the Euclidean space is called *two-convex* if at most one principle curvatures in the outward direction to V is negative.

Equivalently V is two-convex if for any closed plane curve γ in V which is contactable in V the plane region bounded by γ belongs to V .

▮ Let K be a closed set bounded by a smooth surface in \mathbb{R}^4 . Assume K contains two coordinate planes

$$\{(x, y, 0, 0) \in \mathbb{R}^4\} \quad \text{and} \quad \{(0, 0, z, t) \in \mathbb{R}^4\}$$

in its interior and also belongs to the closed 1-neighborhood of these two planes.

Show that the complement of K cannot be two-convex.

Semisolutions

Geodesic hypersurface. Assume Σ is a totally geodesic embedded hypersurface in M . Without loss of generality, we can assume that Σ is connected.

The complement $M \setminus \Sigma$ has one or two connected components. First let us show that if the number of connected components is two, then M is homeomorphic to sphere.

By cutting M along Σ we get two manifolds, say M_1 and M_2 , with geodesic boundaries. Prove that the distance functions to the boundary $f_1: M_1 \rightarrow \mathbb{R}$ and $f_2: M_2 \rightarrow \mathbb{R}$ are strictly convex in the interiors of the manifolds.

Smooth the functions f_i keeping them convex; this can be done by applying Greene–Wu Theorem [see Thm. 2 in 57]. In particular each f_i has single critical point which is its maximum.

Applying Morse lemma, we get that each manifold M_i is homeomorphic to a ball; hence M is homeomorphic to the sphere.

If $M \setminus \Sigma$ is connected, passing to a double cover of M , we reduce the problem to the case which already has been considered. \square

The problem was suggested by Peter Petersen.

If convex, then embedded. Observe first that any closed embedded locally convex hypersurface in a non-positively curved simply connected complete manifold bounds a convex region.

Let Σ be an immersed locally convex hypersurface in M . Set

$$m = \dim \Sigma = \dim M - 1$$

Given a point in p on Σ denote by p_r the point on distance r from p which lies on the geodesic starting from p in the outer normal direction to Σ . For fixed $r \geq 0$, the points p_r sweep an immersed locally convex hypersurface which we denote by Σ_r .

Fix $z \in \Sigma$. Denote by S_r the sphere of radius r centered at z . Note that S_r is diffeomorphic to m -dimensional sphere.

Denote by d the diameter of Σ . Note that for all $r > 0$ any point on Σ_r lies on a distance at most d from S_r . Conclude that for large r the closest point projection $\varphi_r: \Sigma_r \rightarrow S_r$ is an immersion.

Since Σ is connected and $m \geq 2$, it follows that φ_r is a diffeomorphism for all large r .

By the observation above, Σ_r bounds a convex region for all large r . By an open-closed argument, the same holds for all $r \geq 0$. Hence the result follows. \square

The problem is due to Stephanie Alexander [see 58].

Immersed ball. Equip Σ with the induced intrinsic metric. Denote by κ the lower bound for principle curvatures of Σ . Note that we can assume that $\kappa > 0$.

Fix sufficiently small $\varepsilon = \varepsilon(M, \kappa) > 0$. Given $p \in \Sigma$ consider the lift $\tilde{h}_p: B(p, \varepsilon) \rightarrow T_{h(p)}$ along the exponential map $\exp_{h(p)}: T_{h(p)} \rightarrow M$. More precisely:

1. Connect each point $q \in B(p, \varepsilon) \subset \Sigma$ to p by a minimizing geodesic path $\gamma_q: [0, 1] \rightarrow \Sigma$
2. Consider the lifting $\tilde{\gamma}_q$ in $T_{h(p)}$; that is the curve such that $\tilde{\gamma}_q(0) = 0$ and $\exp_{h(p)} \circ \tilde{\gamma}_q(t) = \gamma_q(t)$ for any $t \in [0, 1]$.
3. Set $\tilde{h}(q) = \tilde{\gamma}_q(1)$.

Show that all the hypersurfaces $\tilde{h}_p(B(p, \varepsilon)) \subset T_{h(p)}$ has principle curvatures at least $\frac{\kappa}{2}$.

Use the same idea as in the solution of “Immersed surface” [page 18] to show that one can fix $\delta = \delta(M, \kappa) > 0$ such that the restriction of $\tilde{h}_p|_{B(p, \delta)}$ is injective. Conclude that the restriction $h|_{B(p, \delta)}$ is injective for any $p \in \Sigma$.

Now consider locally equidistant surfaces Σ_t in the inward direction for small t . The principle curvatures of Σ_t remain at least κ in the

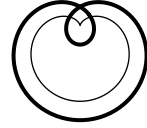
barrier sense. By the same argument as above, any δ -ball in Σ_t is embedded.

Applying open-closed argument we get a one parameter family of locally convex locally equidistant surfaces Σ_t for defined in a maximal interval $[0, a)$ and the surface Σ_a degenerates to a point, say p .

To construct the immersion $\partial\bar{B}^m \looparrowright M$, take the point p as the image of the center \bar{B}^m and take the surfaces Σ_t as the restrictions of the embedding to the spheres; the existence of the immersion follows from the Morse lemma. \square

As you see from the picture, the analogous statement does not hold in the two-dimensional case.

The proof presented above was indicated in the lectures of Mikhael Gromov [see 35]; the proof was written rigorously by Jost Eschenburg in [59].



A variation of Gromov's proof was obtained independently by Ben Andrews in [60]. Instead of equidistant deformation, he uses a so called *inverse mean curvature flow*; this way he has to perform some calculations to show that convexity survives in the flow, but he does not have to worry about non-smoothness of the hypersurfaces.

Minimal surface in the sphere. Fix a geodesic n -dimensional sphere \mathbb{S}^n in \mathbb{S}^m .

Given $r \in (0, \frac{\pi}{2}]$, denote by U_r and \tilde{U}_r the tubular r -neighborhood of Σ and \mathbb{S}^n in \mathbb{S}^m correspondingly.

Prove that $U_{\frac{\pi}{2}} \supset \mathbb{S}^m$. Then it follows that

$$(*) \quad U_{\frac{\pi}{2}} = \tilde{U}_{\frac{\pi}{2}} = \mathbb{S}^m.$$

Prove that for any $x \in \partial U_r$ we have

$$H_r(x) \geq \tilde{H}_r,$$

where $H_r(x)$ denotes the mean curvature of ∂U_r at a point x and \tilde{H}_r is the mean curvature of $\partial \tilde{U}_r$.

Set

$$\begin{aligned} a(r) &= \text{vol}_{m-1} \partial U_r, & \tilde{a}(r) &= \text{vol}_{m-1} \partial \tilde{U}_r, \\ v(r) &= \text{vol}_m U_r, & \tilde{v}(r) &= \text{vol}_m \tilde{U}_r. \end{aligned}$$

by the coarea formula,

$$\frac{d}{dr} v(r) \stackrel{a.e.}{=} a(r), \quad \frac{d}{dr} \tilde{v}(r) = \tilde{a}(r).$$

Note that

$$\begin{aligned}\frac{d}{dr}a(r) &\leq \int_{\partial U_r} H_r(x) \cdot d_x \text{vol}_{m-1} \leq \\ &\leq a(r) \cdot \tilde{H}_r\end{aligned}$$

and

$$\frac{d}{dr}\tilde{a}(r) = \tilde{a}(r) \cdot \tilde{H}_r.$$

It follows that

$$\frac{v''(r)}{v(r)} \leq \frac{\tilde{v}''(r)}{\tilde{v}(r)}$$

for almost all r . Therefore

$$v(r) \leq \frac{\text{area } \Sigma}{\text{area } \mathbb{S}^n} \cdot \tilde{v}(r)$$

for any $r > 0$.

According to (*),

$$v(\frac{\pi}{2}) = \tilde{v}(\frac{\pi}{2}) = \text{vol } \mathbb{S}^m.$$

Whence the result follows. \square

This problem is the most geometric part of the isoperimetric inequality proved by Frederick Almgren in [61]. The argument is similar to the proof of isometric inequality for manifolds with positive Ricci curvature given by Mikhael Gromov in [62].

Hypercurve. Fix $p \in M$. Denote by s the second fundamental form of M at p ; it is a symmetric bi-linear form on the tangent space $T_p M$ of M with values in the normal space $N_p M$ to M . Note that the normal space $N_p M$ is two-dimensional.

Prove that if the sectional curvature of M is positive, then

$$(*) \quad \langle s(X, X), s(Y, Y) \rangle > 0$$

for any pair of nonzero vectors $X, Y \in T_p M$.

Show that (*) implies that there is an orthonormal basis e_1, e_2 in $N_p M$ such that the real-valued quadratic forms

$$s_1(X, X) = \langle s(X, X), e_1 \rangle, \quad s_2(X, X) = \langle s(X, X), e_2 \rangle$$

are positive definite.

Note that the curvature operators R_1 and R_2 , defined by the following identity

$$R_i(X \wedge Y, V \wedge W) = s_i(X, W) \cdot s_i(Y, V) - s_i(X, V) \cdot s_i(Y, W),$$

are positive. Finally, note that $R_1 + R_2$ is the curvature operator of M at p . \square

The problem is due to Alan Weinstein [see 63]. Note that from [64]/[65] it follows that the universal cover of M is homeomorphic/diffeomorphic to a standard sphere.

Horosphere. Set $m = \dim \Sigma = \dim M - 1$.

Let $b: M \rightarrow \mathbb{R}$ be the Busemann function such that $\Sigma = b^{-1}(\{0\})$. Set $\Sigma_r = b^{-1}(\{r\})$, so $\Sigma_0 = \Sigma$.

Let us equip each Σ_r with induced Riemannian metric. Note that all Σ_r have bounded curvature. In particular, the unit ball in Σ_r has volume bounded above by a universal constant, say v_0 .

Given $x \in \Sigma$ denote by γ_x the unit-speed geodesic such that $\gamma_x(0) = x$ and $b(\gamma_x(t)) = t$ for any t . Consider the map $\varphi_r: \Sigma \rightarrow \Sigma_r$ defined as $\varphi_r: x \mapsto \gamma_x(r)$.

Notice that φ_r is a bi-Lipschitz map with the Lipschitz constants $e^{a \cdot r}$ and $e^{b \cdot r}$. In particular, the ball of radius R in Σ is mapped by φ_r to a ball of radius $e^{a \cdot r} \cdot R$ in Σ_r . Therefore

$$\text{vol}_m B(x, R)_\Sigma \leq e^{m \cdot b \cdot r} \cdot \text{vol}_m B(x, e^{a \cdot r} \cdot R)_{\Sigma_r}$$

for any $R, r > 0$. Taking $e^{a \cdot r} \cdot R = 1$, we get

$$\text{vol}_m B(x, R)_\Sigma \leq v_0 \cdot R^{m \cdot \frac{b}{a}}.$$

\square

The problem was suggested by Vitali Kapovitch.

There are examples of horospheres as above with degree of polynomial growth higher than m . For example, consider the horosphere Σ in the complex hyperbolic space of real dimension 4. Clearly $m = \dim \Sigma = 3$, but the degree of its volume growth is 4.

In this case Σ is isometric to the Heisenberg group defined below with a left-invariant metric. It is a good exercise to show that any such metric has volume growth of degree 4.

Heisenberg group is the group of 3×3 upper triangular matrices of the form

$$\begin{pmatrix} 1 & a & c \\ 0 & 1 & b \\ 0 & 0 & 1 \end{pmatrix}$$

under the operation of matrix multiplication.

Minimal spheres. Choose a pair of sufficiently close minimal spheres Σ and Σ' , say assume that the distance a between Σ and Σ' is strictly smaller than the injectivity radius of the manifold. Note that in this case there is a bijection $\Sigma \rightarrow \Sigma'$, which will be denoted by $p \mapsto p'$ such that the distance $|p - p'| = a$ for any $p \in \Sigma$.

Let $\iota_p: T_p \rightarrow T_{p'}$ be the parallel translation along the (necessary unique) minimizing geodesic from p to p' . Use the hairy ball theorem to show that there is a pair (p, p') such that $\iota_p(T_p \Sigma) = T_{p'} \Sigma'$.

Consider pairs of unit-speed geodesics α and α' in Σ and Σ' which start at p and p' correspondingly and go in the parallel directions, say ν and ν' . Set $\ell_\nu(t) = |\alpha(t) - \alpha'(t)|$.

Use the second variation formula to show that $\ell''_\nu(0)$ has negative average for all tangent directions ν to Σ at p . In particular $\ell''_\nu(0) < 0$ for a pair α and α' as above. It follows that there are points $v \in \Sigma$ near p and $v' \in \Sigma'$ near p' such that

$$|v - v'| < |p - p'|;$$

the latter leads to a contradiction. □

It seems pleasurable that a compact positively curved 4-dimensional manifold cannot contain a pair of equidistant spheres. The argument above implies that the distance between such a pair has to exceed the injectivity radius of the manifold.

The problem was suggested by Dmitri Burago. Here is a short list of classical problems with similar solutions:

- ◊ Synge's problem [see 66].
 - *Any compact even-dimensional orientable manifold with positive sectional curvature is simply connected.*
- ◊ Frankel's problems [see 67].
 - *Any two compact minimal hypersurfaces in a Riemannian manifold with positive Ricci curvature must intersect.*
 - *Assume Σ_1 and Σ_2 be two compact geodesic submanifolds in a manifold with positive sectional curvature M and*

$$\dim \Sigma_1 + \dim \Sigma_2 \geq \dim M.$$

Show that $\Sigma_1 \cap \Sigma_2 \neq \emptyset$.

- ◊ Bochner's problem [see 68].
 - *Let (M, g) be a closed Riemannian manifold with negative Ricci curvature. Prove that (M, g) does not admit an isometric \mathbb{S}^1 -action.*

The problem “Geodesic immersion” on page 27 can be considered as further development of the same idea.

Positive curvature and symmetry. Let M be a 4-dimensional Riemannian manifold with isometric \mathbb{S}^1 -action. Consider the quotient space $X = M/\mathbb{S}^1$. Note that X is a positively curved 3-dimensional Alexandrov space. In particular the angle $\angle[x^y_z]$ between any two geodesics $[xy]$ and $[xz]$ is defined and for any non-degenerate triangle $[xyz]$ formed by the minimizing geodesics $[xy]$, $[yz]$ and $[zx]$ in X we have

$$(*) \quad \angle[x^y_z] + \angle[y^z_x] + \angle[z^x_y] > \pi.$$

Assume $p \in X$ corresponds to a fixed point of \mathbb{S}^1 -action. Show that for any three geodesics $[px]$, $[py]$ and $[pz]$ in X we have

$$(**) \quad \angle[p^x_y] + \angle[p^y_z] + \angle[p^z_x] \leq \pi.$$

and

$$(***) \quad \angle[p^x_y], \angle[p^y_z], \angle[p^z_x] \leq \frac{\pi}{2}.$$

Arguing by contradiction, assume that there are 4 fixed points q_1, q_2, q_3 and q_4 . Connect each pair $q_i \neq q_j$ by a minimizing geodesic $[q_i q_j]$.

Denote by ω the sum of all 12 angles of the type $\angle[q_i^{q_j}_{q_k}]$. By $(***)$, each triangle $\triangle q_i q_j q_k$ is non-degenerate. Therefore by $(*)$, we have

$$\omega > 4 \cdot \pi.$$

Applying $(**)$ at each vertex q_i , we have

$$\omega \leq 4 \cdot \pi,$$

a contradiction. □

The problem is due to Wu-Yi Hsiang and Bruce Kleiner [see 69]. The connection of this proof to Alexandrov geometry was noticed by Karsten Grove in [70]. An interesting new twist of this idea is given by Karsten Grove and Burkhard Wilking in [71].

Energy minimizer. Denote by \mathcal{U} the unit tangent bundle over $\mathbb{R}P^m$ and \mathcal{L} the space of projective lines in $\ell: \mathbb{R}P^1 \rightarrow \mathbb{R}P^m$. The spaces \mathcal{U} and \mathcal{L} have dimensions $2 \cdot m - 1$ and $2 \cdot (m - 1)$ correspondingly.

According to Liouville’s theorem, the identity

$$\int_{\mathcal{U}} f(v) \cdot d_v \text{vol}_{2 \cdot m - 1} = \int_{\mathcal{L}} d_\ell \text{vol}_{2 \cdot (m - 1)} \cdot \int_{\mathbb{R}P^1} f(\ell'(t)) \cdot dt$$

holds for any integrable function $f: \mathcal{U} \rightarrow \mathbb{R}$.

Let $F: \mathbb{RP}^m \rightarrow \mathbb{RP}^m$ be a smooth map. Note that up to a multiplicative constant, the energy of F can be expressed the following way

$$\int_{\mathcal{U}} |dF(v)|^2 \cdot d_v \text{vol}_{2m-1} = \int_{\mathcal{L}} d_\ell \text{vol}_{2 \cdot (m-1)} \cdot \int_{\mathbb{RP}^1} |[d(F \circ \ell)](t)|^2 \cdot dt.$$

The result follows since

$$\int_{\mathbb{RP}^1} |[d(F \circ \ell)](t)|^2 \cdot dt \geq \pi$$

for any line $\ell: \mathbb{RP}^1 \rightarrow \mathbb{RP}^m$. □

The problem is due to Christopher Croke [see 72]. He uses the same idea to show that the identity map on \mathbb{CP}^m is energy minimizing in its homotopy class. For \mathbb{S}^m , an analogous statement does not hold if $m \geq 3$. In fact, if a closed Riemannian manifold M has dimension at least 3 and $\pi_1 M = \pi_2 M = 0$, then the identity map on M is homotopic to a map with arbitrary small energy; the latter was shown by Brian White in [73].

The same idea is used to prove Loewner's inequality on the volume in of \mathbb{RP}^m with metric conformally equivalent to the canonical one [see 74].

Curvature vs. injectivity radius. We will show that if the injectivity radius of the manifold (M, g) is at least π , then the average of sectional curvatures on (M, g) is at most 1. This is equivalent to the problem.

Fix a point $p \in M$ and two orthonormal vectors $U, V \in T_p M$. Consider the geodesic γ in M such that $\dot{\gamma}(0) = U$.

Set $U_t = \dot{\gamma}(t) \in T_{\gamma(t)}$ and let $V_t \in T_{\gamma(t)}$ be the parallel translation of $V = V_0$ along γ .

Consider the field $W_t = \sin t \cdot V_t$ on γ . Set

$$\begin{aligned} \gamma_\tau(t) &= \exp_{\gamma(t)}(\tau \cdot W_t), \\ \ell(\tau) &= \text{length}(\gamma_\tau|_{[0, \pi]}), \\ q(U, V) &= \ell''(0). \end{aligned}$$

Note that

$$(*) \quad q(U, V) = \int_0^\pi [(\cos t)^2 - K(U_t, V_t) \cdot (\sin t)^2] \cdot dt,$$

where $K(U, V)$ is the sectional curvature in the direction spanned by U and V .

Since any geodesics of length π is minimizing, we get $q(U, V) \geq 0$ for any pair of orthonormal vectors U and V . It follows that average value of the right hand side in $(*)$ is non-negative.

By Liouville's theorem, while taking the average of $(*)$, we can switch the order of integrals; therefore

$$0 \leq \frac{\pi}{2} \cdot (1 - \bar{K}),$$

where \bar{K} denotes the average of sectional curvatures on (M, g) . Hence the result follows. \square

Liouville's theorem has a number of similar applications, one of the most beautiful is the sharp isoperimetric inequality for 4-dimensional Hadamard manifolds; it was proved by Christopher Croke in [75], see also [76].

Almost flat manifold. First prove that for given $\varepsilon > 0$, there is big enough m and $m \times m$ integer matrix A such that all its eigenvalues are ε -close to 1.

Consider $(m+1)$ -dimensional manifold S obtained from $\mathbb{T}^m \times [0, 1]$ by gluing $\mathbb{T}^m \times 0$ to $\mathbb{T}^m \times 1$ along the map given by A .

Show that S does not admit a finite cover by a nil-manifold.

Assuming that ε is small, show that S admits a metric with curvature and diameter sufficiently small. \square

This example was constructed by Galina Guzhvina in [77].

It is expected that for small enough $\varepsilon > 0$, a Riemannian manifold (M, g) of any dimension with $\text{diam}(M, g) \leq 1$ and $|K_g| \leq \varepsilon$ cannot be simply connected, here K_g denotes the sectional curvature of g . It is not true if instead one asks only have $K_g \leq \varepsilon$; in fact, for any $\varepsilon > 0$, there are metrics g on \mathbb{S}^3 with $K_g \leq \varepsilon$ and $\text{diam}(\mathbb{S}^3, g) \leq 1$; this example was originally constructed by Mikhael Gromov in [54]; a simplified proof was given by Peter Buser and Detlef Gromoll in [11].

Approximation of quotient. Note that G admits an embedding into a compact connected Lie group H , say we can assume $H = \text{SO}(n)$, for large enough n .

Fix a $\kappa \leq 0$ such that the curvature bound of (M, g) is bounded below by κ .

The bi-invariant metric h on H is nonnegatively curved. Therefore for any positive integer n the product $(H, \frac{1}{n} \cdot h) \times (M, g)$ is a Riemannian manifold with curvature bounded below by κ .

The diagonal action of G on $(H, \frac{1}{n} \cdot h) \times (M, g)$ is isometric and free. Therefore the quotient $(H, \frac{1}{n} \cdot h) \times (M, g)/G$ is a Riemannian manifold,

say (N, g_n) . By O’Nail’s formula, (N, g_n) has curvature bounded below by κ .

Clearly, (N, g_n) converge to $(M, g)/G$ as $n \rightarrow \infty$. \square

Some times this construction is called *Cheeger’s trick*, although it was used before Cheeger. The earliest use of this construction I found [78], where it was used to show that Berger’s spheres have positive curvature. This trick is used to construct most of the known examples of positively and non-negatively curved manifolds [see 79–83].

The quotient space $(M, g)/G$ has finite dimension and curvature bounded below in the sense of Alexandrov. It is expected that not all spaces with this property admit approximation by Riemannian manifolds with curvature bounded below, some partial results are discussed in [84, 85].

Polar points. Fix a unit-speed geodesic γ such that $\gamma(0) = p$. Set $p^* = \gamma(\pi)$.

Prove that p^* is a solution. \square

Alternative proof. Assume the contrary; that is, for any $x \in M$ there is a point x' such that

$$|x - x'|_g + |p - x'|_g > \pi.$$

Show that there is a continuous map $x \mapsto x'$ such that the above inequality holds for any x .

Fix sufficiently small $\varepsilon > 0$. Prove that the set $W_\varepsilon = M \setminus B(p, \varepsilon)$ is homeomorphic to a ball and the map $x \mapsto x'$ sends W_ε into itself.

By Brouwer’s fixed-point theorem, $x = x'$ for some x . In this case

$$|x - x'|_g + |p - x'|_g \leq \pi,$$

a contradiction. \square

The problem is due to Anatoliy Milka [see 86].

Isometric section. Arguing by contradiction, assume $\iota: M \rightarrow W$ is an isometric section. It makes possible to treat M as a submanifold in W .

Given $p \in M$, denote by $N_p^1 M$ the sphere of unit normal vectors to M at p . Given $v \in N_p^1$ and real value k , set

$$p^{k \cdot v} = s \circ \exp_p(k \cdot v).$$

Note that

$$(*) \quad p^{0 \cdot v} = p \text{ for any } p \in M \text{ and } v \in N_p^1.$$

Fix sufficiently small $\delta > 0$. By Rauch comparison, if $w \in N_q^1$ is the parallel translation of $v \in N_p^1$ along a minimizing geodesic from p to q in M , then

$$(**) \quad |p^{k \cdot v} - q^{k \cdot w}|_M < |p - q|_M$$

assuming $|k| \leq \delta$. The same comparison implies that

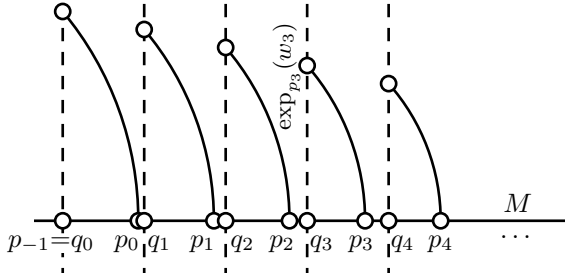
$$(***) \quad |p^{k \cdot v} - q^{k' \cdot w}|_M^2 < |p - q|_M^2 + (k - k')^2$$

assuming $|k|, |k'| \leq \delta$.

Choose p and $v \in N_p^1$ so that $r = |p - p^{\delta \cdot v}|$ takes the maximal possible value. From $(**)$ it follows that $r > 0$.

Let γ be the extension of the unit-speed minimizing geodesic from p_v to p ; denote by v_t the parallel translation of v to $\gamma(t)$ along γ .

We can choose the parameter of γ so that $p = \gamma(0)$, $p^v = \gamma(-r)$. Set $p_n = \gamma(n \cdot r)$, so $p = p_0$ and $p^v = p_{-1}$. Fix large integer N and set $w_n = (1 - \frac{n}{N}) \cdot v_{n \cdot r}$ and $q_n = p_n^{w_n}$.



From $(***)$, there is a constant C independent of N such that

$$|q_k - q_{k+1}| < r + \frac{C}{N^2} \cdot \delta^2.$$

Therefore

$$|q_{k+1} - p_{k+1}| > |q_k - p_k| - \frac{C}{N^2} \cdot \delta^2.$$

By induction, we get

$$|q_N - p_N| > r - \frac{C}{N} \cdot \delta^2.$$

Since N is large we get

$$|q_N - p_N| > 0.$$

By $(*)$ we get $q_N = p_N^0 = p_N$, a contradiction. \square

This proof is the core of the solution of Soul conjecture by Grigori Perelman [see 87].

Warped product. Given $x \in \Sigma$, denote by ν_x the normal vector to Σ at x which agrees with the orientations of Σ and M . Denote by κ_x the non-negative principle curvature of Σ at x ; since Σ is minimal the other principle curvature has to be $-\kappa_x$.

Consider the warped product $W = \mathbb{S}^1 \times_f \Sigma$ for some positive smooth function $f: \Sigma \rightarrow \mathbb{R}$. Assume that a point $y \in W$ projects to a point $x \in \Sigma$. Straightforward computations show that

$$\begin{aligned} \text{Sc}_W(y) &= \text{Sc}_\Sigma(x) - 2 \cdot \frac{\Delta f(x)}{f(x)} = \\ &= \text{Sc}_M(x) - 2 \cdot \text{Ric}(\nu_x) - 2 \cdot \kappa_x^2 - 2 \cdot \frac{\Delta f(x)}{f(x)}. \end{aligned}$$

Consider linear operator L on the space of smooth functions on Σ defined as

$$(Lf)(x) = -[\text{Ric}(\nu_x) + \kappa_x^2] \cdot f(x) - (\Delta f)(x)$$

It is sufficient to find a smooth function f on Σ such that

$$(*) \quad f(x) > 0 \quad \text{and} \quad (Lf)(x) \geq 0$$

for any $x \in \Sigma$.

Fix a smooth function $f: \Sigma \rightarrow \mathbb{R}$. Extend the field $f(x) \cdot \nu_x$ on Σ to a smooth field, say v , on whole M . Denote by ι_t the flow along v for time t and set $\Sigma_t = \iota_t(\Sigma)$.

Informal end of proof. Denote by $H_t(x)$ the mean curvature of Σ_t at $\iota_t(x)$. Note that the value $(Lf)(x)$ is the derivative of the function $t \mapsto H_t(x)$ at $t = 0$.

Therefore the condition $(*)$ means that we can push Σ into one of its sides so that its mean curvature does not increase in the first order. Since Σ is area minimizing, the existence of such push follows; read further if you are not convinced. \square

Formal end of proof. Denote by $\delta(f)$ the second variation of area of Σ_t ; that is consider the area function $a(t) = \text{area } \Sigma_t$ and set $\delta(f) = a''(0)$. Direct calculations show that

$$\begin{aligned} \delta(f) &= \int_{\Sigma} (-[\text{Ric}(\nu_x) + \kappa_x^2] \cdot f^2(x) + |\nabla f(x)|^2) \cdot d_x \text{area} = \\ &= \int_{\Sigma} (Lf)(x) \cdot f(x) \cdot d_x \text{area}. \end{aligned}$$

Since Σ is area minimizing we get

$$(**) \quad \delta(f) \geq 0$$

for any f .

Choose a function f which minimize $\delta(f)$ among all the functions such that $\int_{\Sigma} f^2(x) \cdot d_x \text{area} = 1$. Note that f an eigenfunction for the linear operator L ; in particular f is smooth. Denote by λ the eigenvalue of f ; by $(**)$, $\lambda \geq 0$.

Show that $f(x) > 0$ at any x . Since $Lf = \lambda \cdot f$, the inequalities $(*)$ follow. \square

The problem is due to Mikhael Gromov and Blaine Lawson [see 88]. Earlier, Shing-Tung Yau and Richard Schoen showed that the same assumptions imply existence of conformal factor on Σ which makes it positively curved. Both statement are used to proof that \mathbb{T}^3 does not admit a metric with positive scalar curvature; the original proof is given in [89].

Both statements admit straightforward generalization to higher dimensions and they can be used to show non existence metric with positive scalar curvature on \mathbb{T}^m with $m \leq 7$. For $m = 8$, the proof stops to work since in this dimension the area minimizing hypersurfaces might have singularities. For example, any domain in the cone in \mathbb{R}^8 defined by the identity

$$x_1^2 + x_2^2 + x_3^2 + x_4^2 = x_5^2 + x_6^2 + x_7^2 + x_8^2$$

is area minimizing among the hypersurfaces with the same boundary.

No approximation. Fix an increasing function $\varphi: (0, r) \rightarrow \mathbb{R}$ such that

$$\varphi'' + (n-1) \cdot (\varphi')^2 + C = 0.$$

Note that if $\text{Ric}_{g_n} \geq C$, then the function $x \mapsto \varphi(|p - x|_{g_n})$ is subharmonic. It follows that, for arbitrary array of points p_i and positive reals λ_i the function $f_n: M_n \rightarrow \mathbb{R}$ defined by the formula

$$f(x) = \sum_i \lambda_i \cdot \varphi(|p_i - x|_M)$$

is subharmonic. In particular f_n cannot admit a local minima in M_n .

Passing the limit as $n \rightarrow \infty$, we get that any function $f: \mathbb{R}^m \rightarrow \mathbb{R}$ of the form

$$f(x) = \sum_i \lambda_i \cdot \varphi(|p_i - x|_{\ell_p})$$

does not admit a local minima in \mathbb{R}^m .

Arrive to a contradiction by showing that if $p \neq 2$, then there is an array points p_i and positive reals λ_i such that the function

$$f(x) = \sum_i \lambda_i \cdot \varphi(|p_i - x|_{\ell_p})$$

has strict local minimum. \square

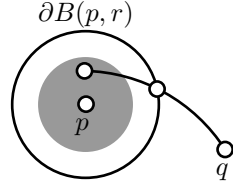
The argument given here is very close to the proof of Abresch–Gromoll inequality in [90]. An alternative solution of this problem can be build on almost splitting theorem proved by Jeff Cheeger and Tobias Colding in [91].

Area of spheres. Fix $r_0 > 0$. Given $r > r_0$, choose a point q on the distance $2 \cdot r$ from p .

Note that any minimizing geodesic from q to a point in $B(p, r_0)$ has to cross $\partial B(p, r)$. By volume comparison, we get that

$$\text{vol } B(p, r_0) \leq C_m \cdot r_0 \cdot \text{area } \partial B(p, r),$$

where C_m is a constant depending only on the dimension $m = \dim M$, say one can take $C_m = 10^m$. \square



Applying the coarea formula, we get that volume growth of M is at least linear and in particular it has infinite volume. The latter was proved independently by Eugenio Calabi and Shing-Tung Yau [see 92, 93].

Curvature hollow. Construct a metric that the connected sum $\mathbb{R}^3 \# \mathbb{S}^2 \times \mathbb{S}^1$ which is flat outside a compact set and has non positive scalar curvature. Further, note that such metric can be constructed in such a way that it has a closed geodesic γ with trivial holonomy and with constant negative curvature in its a tubular neighborhood.

Let us cut tubular neighborhood $\mathbb{D}^2 \times \mathbb{S}^1$ of γ and glue in $\mathbb{S}^1 \times \mathbb{D}^2$ with the swapped factors. Note that after this surgery we get \mathbb{R}^3 .

It remains to construct a metric g on $\mathbb{S}^1 \times \mathbb{D}^2$ with negative scalar curvature which is identical to the original metric on the neighborhood of γ near its boundary. The needed metric $(\mathbb{S}^1 \times \mathbb{D}^2, g)$ can be found among wrap products $\mathbb{S}^1 \times_f \mathbb{D}^2$. \square

This construction was given by Joachim Lohkamp in [94], he describes there yet an other equally simple construction. In fact, this constructions produce \mathbb{S}^1 -invariant hollows with negative Ricci curvature.

On the other hand there are no hollows with positive scalar curvature; the latter is equivalent to the Positive Mass Conjecture.

Flat coordinate planes. Fix $\varepsilon > 0$ such that there is unique geodesic between any two points on distance $< \varepsilon$ from the origin of \mathbb{R}^3 .

Consider three points a , b and c on the coordinate lines which are ε -close to the origin.

Prove that the angles of the triangle $\triangle abc$ coincide with its model angles. It follows that there is a flat geodesic triangle in (\mathbb{R}^3, g) with vertex at a , b and c .

Use the family of constructed flat triangles to show that at any x point in the $\frac{\varepsilon}{10}$ -neighborhood of the origin the sectional curvature vanish in an open set of sectional directions. The latter implies that the curvature is identically zero in this neighborhood.

Moving the origin and apply the same argument we get that the curvature is identically zero everywhere. Hence the result follows. \square

This problem appears in the paper of Dmitri Panov and me [see 95]; it is based on a lemma discovered by Sergei Buyalo in [96].

Two-convexity. *Morse-style solution.* Equip \mathbb{R}^4 with coordinates (x, y, z, t) .

Consider a generic linear function $\ell: \mathbb{R}^4 \rightarrow \mathbb{R}$ which is close to the sum of coordinates $x+y+z+t$. Note that ℓ has non-degenerate critical points on ∂K and all its critical values are different.

Consider the sets

$$W_s = \{ w \in \mathbb{R}^4 \setminus K \mid \ell(w) < s \}.$$

Note that W_{-1000} contains a closed curve, say α , which is contactable in $\mathbb{R}^4 \setminus K$, but not constructable in the set W_{-1000} .

Set s_0 to be the infimum of the values s such that the α is contactable in W_s .

Note that s_0 is a critical value of ℓ on ∂K ; denote by p_0 the corresponding critical point. By 2-convexity of $\mathbb{R}^4 \setminus K$, the index of p_0 has to be at most 1. On the other hand, since the disc hangs at this point, its index has to be at least 2, a contradiction. \square

Alexandrov-style proof. Fix a constant metric g on \mathbb{R}^4 . According to the main result of Alexander Bishop and Berg in [97], $X_g = (\mathbb{R}^4 \setminus (\text{Int } K), g)$ has non-positive curvature in the sense of Alexandrov. In particular the universal cover of \tilde{X}_g of X_g is a CAT[0] space.

By rescaling g and passing to the limit we obtain that universal Riemannian cover Z_g of (\mathbb{R}^4, g) branching in the coordinate planes is a CAT[0] space. Show that Z_g is CAT[0] space if and only if the

two planes are orthogonal with respect to g ; the latter leads to a contradiction. \square

The Morse-style proof is based on the idea described by Mikhael Gromov in [35, §2].

Note that the closed 1-neighborhood of these two planes has two-convex complement, but the boundary of this neighborhood is not smooth.

Chapter 4

Curvature free differential geometry

This chapter we consider mostly Riemannian manifolds without curvature bounds.

The reader should be familiar with main technique including some symplectic geometry, in particular that geodesic flow preserves the volume on the tangent bundle.

Besikovitch inequality

▮ *Let g be a Riemannian metric on an m -dimensional cube $Q = [0, 1]^m$ such that any curve connecting opposite faces has length at least 1. Prove that $\text{vol}(Q, g) \geq 1$, and equality holds if and only if (Q, g) is isometric to the unit cube.*

Semisolution. Set

$$A_i = \{ (x_1, x_2, \dots, x_m) \in [0, 1]^m \mid x_i = 0 \}.$$

Consider functions $f_i: [0, 1]^m \rightarrow \mathbb{R}$ defined by $f_i(x) = \text{dist}_{A_i} x$. Note that the map $\mathbf{f}: ([0, 1]^m, g) \rightarrow \mathbb{R}^m$ defined as

$$\mathbf{f}: x \mapsto (f_1(x), f_2(x), \dots, f_m(x))$$

is Lipschitz.

Prove that Jacobian of \mathbf{f} is at most 1 and $\mathbf{f}([0, 1]^m) \supset [0, 1]^m$. Therefore

$$\text{vol}(Q, g) \geq \text{vol}([0, 1]^m) = 1.$$

The equality case is left for the reader. \square

The inequality was proved by Abram Besikovitch in [98]. It has number applications in Riemannian geometry. For example using this inequality it is easy to solve the following problem.

- \diamond Assume a metric g on \mathbb{R}^m coincides with Euclidean outside of a bounded set K ; assume further that any geodesic which comes into K goes out from K the same way as if the metric would be Euclidean everywhere. Show that g is flat.

Minimal foliation⁺

The minimal surface in Riemannian manifolds are defined on page 28.

\boxtimes Consider $\mathbb{S}^2 \times \mathbb{S}^2$ equipped with a Riemannian metric g which is C^∞ -close to the product metric. Prove that there is a conformally equivalent metric $\lambda \cdot g$ and re-parametrization of $\mathbb{S}^2 \times \mathbb{S}^2$ such that each sphere $\mathbb{S}^2 \times x$ and $y \times \mathbb{S}^2$ forms a minimal surface in $(\mathbb{S}^2 \times \mathbb{S}^2, \lambda \cdot g)$.

The solution requires pseudo-holomorphic curves introduced by Mikhael Gromov in [99].

Volume and convexity⁺

A function f defined on Riemannian manifold is called convex if for any geodesic γ , the composition $f \circ \gamma$ is a convex real-to-real function.

\boxtimes Let M be a complete Riemannian manifold which admits a non-constant convex function. Prove that M has an infinite volume.

The Liouville's theorem which states that geodesic flow on the tangent bundle to a Riemannian manifold preserves the volume form should help to solve this problem.

Sasaki metric

Let (M, g) be a Riemannian manifold. The Sasaki metric is the most natural choice of metric on the tangent space TM . It is uniquely defined by the following properties:

- (i) The natural projection $\tau: TM \rightarrow M$ is a Riemannian submersion.
- (ii) The metric on each tangent space $T_p \subset TM$ is the Euclidean metric induced by g .
- (iii) Assume $\gamma(t)$ is a curve in M and $v(t) \in T_{\gamma(t)}$ is a parallel vector field along γ . Note that $v(t)$ forms a curve in TM and $T_{\gamma(t)}M$ forms a submanifold in TM . For the Sasaki metric, we have $\dot{v}(t) \perp T_{\gamma(t)}M$ for any t .

A more constructive way to describe Sasaki metric is given by identifying $T_u[TM]$ for any $u \in T_pM$ with the direct sum of so called vertical and horizontal vectors $T_pM \oplus T_pM$. The projection of this splitting defined by the differential of τ and the Levi-Civita connection. Then $T_u[TM]$ is equipped with the metric defined as

$$\hat{g}(X, Y) = g(X^V, Y^V) + g(X^H, Y^H),$$

where $X^V, X^H \in T_pM$ denotes the vertical and horizontal components of $X \in T_u[TM]$.

▣ Consider the tangent bundle TS^2 equipped with Sasaki metric \hat{g} induced by a Riemannian metric g on S^2 . Show that (TS^2, \hat{g}) lies on bounded Gromov–Hausdorff distance to the ray.

Distant involution

▣ Construct a Riemannian metric g on S^3 and an involution $\iota: S^3 \rightarrow S^3$ such that $\text{vol}(S^3, g)$ is arbitrary small and

$$|x - \iota(x)|_g > 1$$

for any $x \in S^3$.

Normal exponential map[◦]

Let (M, g) be a Riemannian manifold; denote by TM the tangent bundle over M and by $T_p = T_pM$ the tangent space at point $p \in M$.

Given a vector $v \in T_pM$ denote by γ_v the geodesic in (M, g) such that $\gamma(0) = p$ and $\gamma'(0) = v$. The map $\exp: TM \rightarrow M$ defined by $v \mapsto \gamma_v(1)$ is called exponential map.

The restriction of \exp to the T_p is called *exponential map at p* and denoted as \exp_p .

Given a smooth submanifold $S \subset M$; denote by NS the normal bundle over S . The restriction of \exp to NS is called *normal exponential map* of S and denoted as \exp_S .

▣ Let M, N be complete connected Riemannian manifolds. Assume N is immersed into M . Show that the image of the normal exponential map of N is dense in M .

Symplectic squeezing in the torus

▣ Let

$$\omega = dx_1 \wedge dy_1 + dx_2 \wedge dy_2$$

be the standard symplectic form on \mathbb{R}^4 . Assume \mathbb{Z}^2 is the integer lattice in (x_1, y_1) coordinate plane of \mathbb{R}^4 .

Show that an arbitrary bounded domain $\Omega \subset (\mathbb{R}^4, \omega)$ admits a symplectic embedding into $(\mathbb{R}^4, \omega)/\mathbb{Z}^2$.

Diffeomorphism test^o

▣ Let M and N be complete m -dimensional simply connected Riemannian manifolds. Assume $f: M \rightarrow N$ is a smooth map such that

$$|df(v)| \geq |v|$$

for any tangent vector v of M . Show that f is a diffeomorphism.

Volume of tubular neighborhoods

▣ Assume M and M' be isometric closed smooth submanifolds in \mathbb{R}^m . Show that for all small r we have

$$\text{vol } B_r(M) = \text{vol } B_r(M'),$$

where $B_r(M)$ denotes the r -neighborhood of M .

Disc^{*}

▣ Given a big real number L , construct a Riemannian metric g on the disc \mathbb{D} with

$$\text{diam}(\mathbb{D}, g) \leq 1 \quad \text{and} \quad \text{length } \partial\mathbb{D} \leq 1$$

such that any null-homotopy of the boundary in (\mathbb{D}, g) has a curve of length at least L .

Shortening homotopy

▣ Let M be a compact Riemannian manifold with diameter D . Assume that for some $L > D$, there are no geodesic loops in M with length in the interval $(L - D, L + D]$. Show that for any path γ_0 in (M, g) there is a homotopy γ_t rel. to the ends such that

a) $\text{length } \gamma_1 < L$;

b) $\text{length } \gamma_t \leq \text{length } \gamma_0 + 2 \cdot D$ for any $t \in [0, 1]$.

Convex hypersurface

☞ Let M be a hypersurface in a closed Riemannian m -dimensional manifold W . Assume M is geodesic and convex and its injectivity radius is at least 1. Show that there is a point in W which lies on a distance at least $\frac{1}{2 \cdot (m+1)}$ from M .

Almost constant function

☞ Assume $\varepsilon > 0$ is given. Show that there is a positive integer m such that for any closed m -dimensional Riemannian manifold M and any smooth 1-Lipschitz function $f: M \rightarrow \mathbb{R}$ the following holds.

◇ For a random unit-speed geodesic γ in M the event

$$|f \circ \gamma(0) - f \circ \gamma(1)| > \varepsilon$$

happens with probability at most ε .

Here random means that $\gamma'(0)$ takes the random value in the unit tangent bundle of M for the natural choice of distribution.

Bounded curvature

Denote by \mathcal{R} the space of all Riemannian metrics on \mathbb{S}^5 with absolute value of sectional curvature at most 1, and injectivity radius at least 1.

It is easy to see that any metric $g_1 \in \mathcal{R}$ can be connected to the canonical metric g_0 on \mathbb{S}^5 by a continuous family of metrics g_t where $t \in [0, 1]$. The one parameter family of metrics g_t can be found among the metrics of the type

$$g_t = a(t) \cdot g_0 + b(t) \cdot g_1,$$

where $a, b: [0, 1] \rightarrow \mathbb{R}$ are smooth functions such that $a(0) = 1 = b(1)$ and $a(1-s) = 0 = b(s)$ for $s \leq \frac{1}{3}$. In order to keep the bounds on the curvature and injectivity radius, the functions a and b suppose to take huge values in the middle of interval.

☞ Fix a fast growing function, say

$$\Phi(x) = 1000^{1000 \cdot (x+1000)}.$$

Show that there is a metric g_1 such that for any family g_t as above

$$\max_{t \in [0,1]} \{\text{vol}(g_t)\} > \Phi(\text{vol}(g_1)).$$

The solution requires Novikov theorem on the algorithmic undecidability of the problem of recognition of the sphere \mathbb{S}^m for $m \geq 5$. A detailed proof of this theorem can be found in [100].

Semisolutions

Minimal foliation. First show that there is a self-dual harmonic 2-form on $(\mathbb{S}^2 \times \mathbb{S}^2, g)$; that is, a 2-form ω such that $d\omega = 0$ and $\star\omega = \omega$, where \star denotes the Hodge star operator.

Fix $p \in \mathbb{S}^2 \times \mathbb{S}^2$. Use the identity $\star\omega_p = \omega_p$ to show that there is a real number λ_p and the isometry $J_p: T_p \rightarrow T_p$ such that $J_p \circ J_p = -\text{id}$ and $\omega(X, Y) = \lambda_p \cdot g(X, J_p Y)$ for any $X, Y \in T_p$.

Consider canonical symplectic form ω_0 on $\mathbb{S}^2 \times \mathbb{S}^2$; that is sum of pullbacks of volume forms on \mathbb{S}^2 for the two projections $\mathbb{S}^2 \times \mathbb{S}^2 \rightarrow \mathbb{S}^2$. Note that for the canonical metric on $\mathbb{S}^2 \times \mathbb{S}^2$, the form ω_0 is harmonic and self-dual. Since g is close to the standard metric, we can assume that ω is close to ω_0 . In particular $\lambda_p \neq 0$ for any $p \in \mathbb{S}^2 \times \mathbb{S}^2$.

It follows that ω defines symplectic structure on $\mathbb{S}^2 \times \mathbb{S}^2$ and J is its pseudo-complex structure. It remains to take the re-parametrization of $\mathbb{S}^2 \times \mathbb{S}^2$ so that vertical and horizontal spheres will form pseudo-holomorphic curves in the homology classes of $\mathbb{S}^2 \times x$ and $x \times \mathbb{S}^2$. \square

Comments. For general metric the form ω might vanish at some points; if the metric is generic, then it happens on disjoint circles [see 101].

Volume and convexity. Assume the contrary; that is, there is a complete Riemannian manifold M with finite volume which admits a convex function f .

Denote by $\tau: UM \rightarrow M$ the unit tangent bundle over M . Clearly $\text{vol}(UM)$ is finite.

Note that there is a nonempty bounded open set $\Omega \subset UM$ such that $df(u) > \varepsilon$ for any $u \in \Omega$ and some fixed $\varepsilon > 0$.

Denote by φ^t the geodesic flow on UM . By Liouville's theorem

$$\text{vol}[\varphi^t(\Omega)] = \text{vol } \Omega$$

for any t .

Given $u \in \Omega$, consider the function $h: t \mapsto f \circ \tau \circ \varphi^t(u)$. Note that $h'(t) > \varepsilon$ for any $t \geq 0$. It follows that there is an infinite sequence of positive reals t_1, t_2, \dots such that

$$\varphi^{t_i}(\Omega) \cap \varphi^{t_j}(\Omega) = \emptyset$$

if $i \neq j$. The latter implies that $\text{vol}(UM) = \infty$, a contradiction. \square

The idea in the proof is the same as in Poincaré recurrence theorem.

The problem is due to Richard Bishop and Barrett O'Neill [see 102], it was generalized by Shing-Tung Yau in [103].

Sasaki metric. Show that there is a constant ℓ such that for any two unit tangent vectors $v \in T_p\mathbb{S}^2$ and $w \in T_q\mathbb{S}^2$ there is a path $\gamma: [0, 1] \rightarrow \mathbb{S}^2$ from p to q such that

$$\text{length } \gamma \leq \ell$$

and w is the parallel transformation of v along γ .

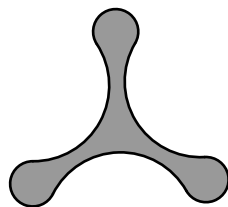
Note that once it is proved, it follows that diameter of the set of all vectors of fixed length in $T\mathbb{S}^2$ has diameter at most ℓ ; in particular the map $T\mathbb{S}^2 \rightarrow [0, \infty)$ defined as $v \mapsto |v|$ preserves the distance with the maximal error ℓ . Hence the result follows.

Distant involution. Given $\varepsilon > 0$, construct a disc D in the plane with

$$\text{length } \partial D < 10 \quad \text{and} \quad \text{area } D < \varepsilon$$

which admits an continuous involution ι such that

$$|\iota(x) - x| \geq 1$$



for any $x \in \partial D$. An example of D can be guessed from the picture.

Take the product $D \times D \subset \mathbb{R}^4$; it is homeomorphic to the 4-ball. Note that

$$\text{vol}_3[\partial(D \times D)] = 2 \cdot \text{area } D \cdot \text{length } \partial D < 20 \cdot \varepsilon.$$

The boundary $\partial(D \times D)$ homeomorphic to \mathbb{S}^3 and the restriction of the involution $(x, y) \mapsto (\iota(x), \iota(y))$ has the needed property.

It remains to smooth $\partial(D \times D)$. □

This example is given by Christopher Croke in [104].

It is instructive to show that for \mathbb{S}^2 such thing is not possible.

Note that according to systolic inequality, the involution ι above cannot be made isometric [see 74].

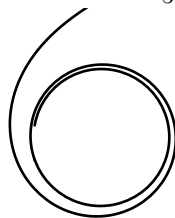
Normal exponential map. Assume the contrary; that is, there is a point $p \in M$ such that the image of normal exponential map to N does not touch ε -neighborhood of p .

Show that given $R > 0$ there is $\delta > 0$ such that if $x \in N$ and $|p - x|_M < R$, then there is a unit speed curve in N which moves to p with velocity at least δ . (In fact, the value δ depends on ε , R and the curvature bounds in $B(p, R)$.)

Following this curve for sufficient time brings us to p ; that is, $p \in N$, a contradiction. □

The problem was suggested by Alexander Lytchak.

From the picture, you should guess an example of immersion such that one point does not lie in the image of the corresponding normal exponential. It might be interesting to see in more details which sets can be avoided by such images.



Symplectic squeezing in the torus. Equip \mathbb{R}^4 with (x_1, y_1, x_2, y_2) -coordinates so that

$$\omega = dx_1 \wedge dy_1 + dx_2 \wedge dy_2$$

is the symplectic form.

The embedding will be given as a composition of a linear symplectomorphism λ with the quotient map $\varphi: \mathbb{R}^4 \rightarrow \mathbb{T}^2 \times \mathbb{R}^2$ by the integer (x_1, y_1) -lattice. Clearly $\varphi \circ \lambda$ preserves the symplectic structure, it remains to find λ such that the restriction $\varphi \circ \lambda|_{\Omega}$ is injective.

Without loss of generality, we can assume that Ω is a ball centered at the origin. Choose an oriented 2-dimensional subspace V subspace of \mathbb{R}^4 such that the integral of ω over $\Omega \cap V$ is small positive number, say $\frac{\pi}{4}$.

Note that there is a linear symplectomorphism λ which maps planes parallel to V to planes parallel to the (x_1, y_1) -plane, and that maps the disk $V \cap \Omega$ to a disk. It follows that the intersection of $\lambda(\Omega)$ with any plane parallel to the (x_1, y_1) -plane is a disk of radius at most $\frac{1}{2}$. In particular $\varphi \circ \lambda|_{\Omega}$ is injective. \square

This construction is given by Larry Guth in [105] and attributed to Leonid Polterovich.

Note that according to the Gromov's non-squeezing theorem in [99], an analogous statement with $\mathbb{C} \times \mathbb{D}$ as the target does not hold, here $\mathbb{D} \subset \mathbb{C}$ is the open disc with the induced symplectic structure. In particular, it shows that the projection of $\lambda(\Omega)$ as above to (x_1, y_1) -plane cannot be made arbitrary small.

Diffeomorphism test. Since N is simply connected, it is sufficient to show that $f: M \rightarrow N$ is a covering map.

Note that f is an open immersion. Let h be the pullback metric on M for $f: M \rightarrow N$. Clearly $h \geq g$. In particular (M, h) is complete and the map $f: (M, h) \rightarrow N$ is a local isometry.

It remains to prove that any local isometry between complete connected Riemannian manifolds of the same dimension is a covering map. \square

Volume of tubular neighborhoods. Let us denote by NM and TM the normal and tangent bundle of M in \mathbb{R}^m .

Consider the the normal exponential map $\exp_M: NM \rightarrow \mathbb{R}^m$ and denote by J_V its Jacobian at $V \in N_p M$. Note that for all small $\varepsilon > 0$, we have

$$(*) \quad \text{vol } B_\varepsilon(M) = \int_M d_p \text{vol}_m \cdot \int_{B(0,r)_{N_p M}} J_V \cdot d_V \text{vol}_{n-m}.$$

Set $m = \dim M$. Given $p \in M$, denote by $s_p: T_p \times T_p \rightarrow N_p$ the second fundamental form of M . Recall that the curvature tensor of M at p can be expressed the following way

$$R_p(X \wedge Y), V \wedge W = \langle s_p(X, W), s_p(Y, V) \rangle - \langle s_p(X, V), s_p(Y, W) \rangle.$$

Given $V \in N_p M$, express J_V in terms of $\langle s_p(X, Y), V \rangle$. Show that for small r the integral

$$v(r) = \int_{B(0,r)_{N_p M}} J_V \cdot d_V \text{vol}_{n-m}$$

is a polynomial of r and its coefficients can be expressed in terms of the curvature tensor R_p .

It follows that the right hand side in $(*)$ can be expressed in terms of curvature tensor of M . The problem follows since the curvature tensor can be expressed in terms of metric tensor of M . \square

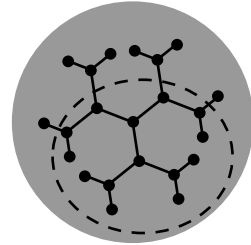
The formula for volume of tubular neighborhood was given by Hermann Weyl in [106].

Disc. Show that given a positive integer n one can construct a tree T embedded into the disc such that any homotopy of the boundary of the disc to a point pass through a curve which intersects n different edges. (For the tree on the diagram $n = 3$.)

Fix small $\varepsilon > 0$, say $\varepsilon = \frac{1}{10}$. Consider the disc with embedded tree T as above. We will construct a metric on the disc with diameter and length of its boundary below 1 such that the distance between any two edges of T of without common vertex is at least ε .

To construct such a metric, fix a metric on the cylinder $\mathbb{S}^1 \times [0, 1]$ such that

- ◊ The ε -neighborhoods of the boundary components have product metrics.



- ◇ Any vertical segment $x \times [0, 1]$ has length $\frac{1}{2}$.
- ◇ One of the boundary component has length ε .
- ◇ The other boundary component has length $2 \cdot m \cdot \varepsilon$, where m is the number of edges in T .

Equip T with a length-metric so that each edge has length ε and glue the long boundary component of the cylinder to T by piecewise isometry so that the resulting space is homeomorphic to disc and the tree corresponds to it-self.

According to the first construction, for any null-homotopy of the boundary the least length is at least $n \cdot \frac{\varepsilon}{10}$. The obtained metric is not Riemannian, but is easy to smooth. Since n is arbitrary the result follows. \square

This example was constructed by Sidney Frankel and Mikhail Katz in [107].

Shortening homotopy. Set

$$p = \gamma_0(0) \text{ and } \ell_0 = \text{length } \gamma_0.$$

By compactness argument, there exists $\delta > 0$ such that no geodesic loops based at p with has length in the interval $(L - D, L + D + \delta]$.

Assume $\ell_0 \geq L + \delta$. Choose $t_0 \in [0, 1]$ such that

$$\text{length}(\gamma_0|_{[0, t_0]}) = L + \delta$$

Let σ be a the minimizing geodesic from $\gamma(t_0)$ to p . Note that γ_0 is homotopic to the joint

$$\gamma'_0 = \gamma_0|_{[0, t_0]} * \sigma * \bar{\sigma} * \gamma|_{[t_0, 1]},$$

where $\bar{\sigma}$ denotes the backward parametrization of σ .

Consider the loop λ_0 at p formed by joint of $\gamma|_{[0, t_0]}$ and σ . Applying a curve shortening process to λ_0 , we get a curve shortening homotopy λ_t rel. its ends from the loop λ_0 to a geodesic loop λ_1 at p . From above,

$$\text{length } \lambda_1 \leq L - D.$$

The joint $\gamma_t = \lambda_t * \bar{\sigma} * \gamma|_{[t_0, 1]}$ is a homotopy from γ'_0 to an other curve γ_1 . From the construction it is clear that

$$\begin{aligned} \text{length } \gamma_t &\leq \text{length } \gamma_0 + 2 \cdot \text{length } \sigma \leq \\ &\leq \text{length } \gamma_0 + 2 \cdot D \end{aligned}$$

for any $t \in [0, 1]$ and

$$\begin{aligned} \text{length } \gamma_1 &= \text{length } \lambda_1 + \text{length } \sigma + \text{length } \gamma|_{[t_0, 1]} \leq \\ &\leq L - D + D + \text{length } \gamma - (L + \delta) = \\ &= \ell_0 - \delta. \end{aligned}$$

Repeating the procedure few times we get we get curves $\gamma_2, \gamma_3, \dots, \gamma_n$ joint by the needed homotopies so that $\ell_{i+1} \leq \ell_i - \delta$ and $\ell_n < L + \delta$, where $\ell_i = \text{length } \gamma_i$.

If $\ell_n \leq L$, we are done. Otherwise repeat the argument once more for $\delta' = \ell_n - L$. \square

The problem is due to Alexander Nabutovsky and Regina Rotman [see 108].

It is not at all easy to find an example of a manifold which satisfy the above condition for some L ; they are found among the Zoll spheres by Florent Balachev, Christopher Croke and Mikhail Katz [see 109].

Convex hypersurface. Let h be the maximal distance from points in W to M .

Fix a fine triangulation of W so that M becomes a sub-complex. Say, let us assume that the diameter of each simplex in τ is less than ε . We can assume that τ is a barycentric subdivision of an other triangulation, so all the vertices of τ can be colored into colors $(0, \dots, m+1)$ in such a way that the vertices of each simplex get different colors. Denote by τ_i the maximal i -dimensional sub-complex of τ with all the vertices colored by $0, \dots, i$.

For each vertex v in τ choose a point $v' \in M$ on the distance $\leq h$. Note that if v and w are the vertices of one simplex, then

$$|v' - w'|_M < 2 \cdot h + \varepsilon.$$

If $\frac{1}{2 \cdot (m+1)} > h$, take $\varepsilon < \frac{1}{2 \cdot (m+1)} - h$. Let us extend the map $v \mapsto v'$ to a continuous map $W \rightarrow M$. The map is already defined on τ_0 . Using the cone construction we can extend it to τ_1 ; we can do this since the distance between vertices in one simplex are below injectivity radius of M . Repeat the cone construction recursively, to extend the map to $\tau_2, \dots, \tau_{m+1} = \tau$; some distance estimates are needed here.

It follows that fundamental class of M vanish in the homology ring of M , a contradiction. \square

This problem is a stripped version of the bound on filling radius given by Mikhael Gromov in [74].

Almost constant function. Given a positive integer m , denote by δ_m the expected value $|x_1|$ of a unit vector $\mathbf{x} = (x_1, \dots, x_m) \in \mathbb{R}^m$ with respect to the uniform distribution.

Observe that $\delta_m \rightarrow 0$ as $m \rightarrow \infty$.

Equip the unit tangent bundle UM of M with the natural probability measure. Since f is 1-Lipschitz, for a random vector v in UM , the expected value of $|df(w)|$ is at most δ_m .

Note that

$$\begin{aligned} |f \circ \gamma(1) - f \circ \gamma(0)| &= \left| \int_0^1 df(\dot{\gamma}(t)) \cdot dt \right| \leq \\ &\leq \int_0^1 |df(\dot{\gamma}(t))| \cdot dt. \end{aligned}$$

Assume $\dot{\gamma}(0)$ takes random value in UM . By Liouville's theorem, the same holds for $\dot{\gamma}(t)$ for any fixed t . Therefore the expected value of

$$\int_0^1 |df(\dot{\gamma}(t))| \cdot dt$$

is at most δ_m .

By Markov's inequality, the probability of the event

$$|f \circ \gamma(1) - f \circ \gamma(0)| > \varepsilon$$

is at most $\frac{\delta_m}{\varepsilon}$. Hence the result follows. \square

I learned the problem from Mikhael Gromov. It gives an example of so called *concentration of measure phenomenon* introduced by Vitali Milman.

Bounded curvature. Show that there is an algorithm to estimate the Gromov–Hausdorff distance between two Riemannian manifolds given in any reasonable way.

Show that if two manifolds with bounded curvature are sufficiently close to each other then they are diffeomorphic.

Now assume contrary; that is for any metric $g_1 \in \mathcal{R}$ there is a path g_t in \mathcal{R} connecting the canonical metric g_0 to g_1 such that

$$\text{vol } g_t \leq \Phi(\text{vol } g_1).$$

If a 5-dimensional Riemannian manifold M with curvature between ± 1 is diffeomorphic to S^5 then it can be described by a metric g_1 in \mathcal{R} . Let g_t be the path as above.

Construct a finite set $F \subset \mathcal{R}$ which is sufficiently dense in the set of metrics in \mathcal{R} with volume at most $\Phi(\text{vol } g_1)$. The path g_t as above can be approximated by a sequence of metrics from F .

Using the algorithms above one can list all such sequences. It implies existence of algorithm which recognize S^5 among 5-dimensional manifolds. The later contradicts Novikov theorem. \square

Instead of function Φ one can take any Turing computable function. The problem and number of its generalizations are due to Alexander Nabutovsky [see 110].

Chapter 5

Metric geometry

In this chapter, we consider metric spaces. All the necessary material could be found in the first three chapters of the textbook [111] by Dmitry Burago, Yuri Burago and Sergei Ivanov.

Let us fix a few standard notations.

- ◇ The distance between two points x and y in a metric space X will be denoted as

$$|x - y|_X.$$

- ◇ A metric space X is called *length space* if for any $\varepsilon > 0$ two points $x, y \in X$ can be connected by a curve α such that

$$\text{length } \alpha < |x - y|_X + \varepsilon.$$

Embedding of a compact

▮ *Prove that any compact metric space is isometric to a subset of a compact length space.*

Semisolution. Let K be a compact metric space. Denote by $B(K)$ the space of bounded functions on K equipped with sup norm; that is,

$$|f| = \sup_{x \in K} |f(x)|.$$

Note that the map $\varphi: K \rightarrow B(K)$, defined by $x \mapsto \text{dist}_x$ is a distance preserving embedding.

Denote by W the linear convex hull of the image $\varphi(K) \subset B(K)$ with the metric induced from $B(K)$. It remains to show that W forms a compact length space. \square

The map φ is called *Kuratowski embedding*, it was constructed in [112], although essentially the same map was described by Maurice Fréchet in the same paper he introduced metric spaces [see 113].

Non-contracting map[◦]

☞ Let K be a compact metric space and

$$f: K \rightarrow K$$

be a non-contracting map. Prove that f is an isometry.

Horo-compactification[◦]

Let X be a metric space. Denote by $C(X, \mathbb{R})$ the space of continuous real-valued functions equipped with the compact open topology.

Fix a point $z_0 \in X$. Given a point $z \in X$, let $f_z \in C(X, \mathbb{R})$ be the function defined as

$$f_z(x) = |z - x|_X - |z - z_0|_X.$$

Let $F_X: X \rightarrow C(X, \mathbb{R})$ be the map defined as $F_X: z \mapsto f_z$.

Denote by \bar{X} the closure of $F_X(X)$ in $C(X, \mathbb{R})$; note that \bar{X} is compact. That is, if F_X is an embedding, then \bar{X} forms a compactification of X , which is called *horo-compactification*. The complement $\partial_\infty X = \bar{X} \setminus F_X(X)$ is called *horo-absolute* of X . The compactification and absolute was introduced by Mikhael Gromov in [114].

☞ Construct a proper metric space X such that F_X is not an embedding. Show that there are no such examples among proper length spaces.

Ball and sphere

☞ Construct a sequence of Riemannian metrics on \mathbb{S}^3 which converges in the Gromov–Hausdorff topology to the unit ball in \mathbb{R}^3 .

Macro-dimension[◦]

Let X be a locally compact metric space m is an integer and $a > 0$. We say that the macro-dimension of X at the scale a is at most m if there is a continuous map f from X to an m -dimensional simplicial complex K such that for any $k \in K$ the inverse image $f^{-1}(\{k\})$ has diameter less than a .

If macro-dimension of X at the scale a is at most m , but not at most $m - 1$, we say that m is the *macro-dimension* of X at the scale a .

Equivalently, the macro-dimension of X on scale a can be defined as the least integer m such that X admits an open covering with diameter of each set less than a and such that each point in X is covered by at most $m + 1$ sets in the cover.

▣ Let M be a simply connected Riemannian manifold with the following property: any closed curve is null-homotopic in its own 1-neighborhood. Prove that the macro-dimension of M on the scale 100 is at most 1.

No short embedding*

▣ Construct a length-metric d on \mathbb{R}^3 , such that for any open set $U \subset \mathbb{R}^3$, there is no short embeddings $(U, d) \rightarrow \mathbb{R}^3$, where \mathbb{R}^3 equipped with the canonical metric.

Sub-Riemannian sphere⁺

Let us define sub-Riemannian metric.

Fix a Riemannian manifold (M, g) . Assume that in the tangent bundle TM a choice of sub-bundle H is given; the sub-bundle H which will be called *horizontal distribution*. The tangent vectors which lie in H will be called *horizontal*. A piecewise smooth curve will be called *horizontal* if all its tangent vectors are horizontal.

The sub-Riemannian distance between points x and y is defined as infimum of lengths of horizontal curves connecting x to y .

Alternatively, the distance can be defined as a limit of Riemannian distances for the metrics

$$g_\lambda(X, Y) = g(X^H, Y^H) + \lambda \cdot g(X^V, Y^V)$$

as $\lambda \rightarrow \infty$, where X^H denotes the horizontal part of X ; that is, the orthogonal projection of X to H and X^V denotes the vertical part of X ; so, $X^V + X^H = X$.

One usually adds a condition which ensure that any curve in M can be arbitrary well approximated by a horizontal curve with the same endpoints. (In particular this ensures that the distance will not take infinite values.) The most common condition is so called *complete non-integrability*; it means that for any $x \in M$, one can choose a basis in $T_x M$ from the vectors of the following type: $A(x)$,

$[A, B](x)$, $[A, [B, C]](x)$, $[A, [B, [C, D]]](x), \dots$ where all vector fields A, B, C, D, \dots are horizontal.

☞ Prove that any sub-Riemannian metric on the \mathbb{S}^m is isometric to the intrinsic metric of a hypersurface in \mathbb{R}^{m+1} .

It will be hard to solve the problem without knowing proof of Nash–Kuiper theorem on length preserving C^1 -embeddings. The original papers of John Nash and Nicolaas Kuiper [see 115, 116] are very readable.

Length-preserving map⁺

A continuous map $f: X \rightarrow Y$ between metric spaces is called *length-preserving* if it preserves the length of curves; that is for any curve α in X we have

$$\text{length}(f \circ \alpha) = \text{length } \alpha.$$

☞ Show that there is no length-preserving map $\mathbb{R}^2 \rightarrow \mathbb{R}$.

The Rademacher’s theorem on differentiability of Lipschitz maps should help to solve this problem.

Fixed segment

☞ Let $\rho(x, y) = \|x - y\|$ be a metric on \mathbb{R}^m induced by a norm $\|\cdot\|$.

Assume that $f: (\mathbb{R}^m, \rho) \rightarrow (\mathbb{R}^m, \rho)$ is an isometry which fixes two distinct points. Show that f fixes the line segment between them.

Pogorelov’s construction^o

☞ Let μ be a regular centrally symmetric finite measure on \mathbb{S}^2 which is positive on every open set. Given two points $x, y \in \mathbb{S}^2$, set

$$\rho(x, y) = \mu[B(x, \frac{\pi}{2}) \setminus B(y, \frac{\pi}{2})].$$

Show that ρ is a length-metric on \mathbb{S}^2 and moreover, geodesics in this metric formed by arcs of great circles.

Straight geodesics

☞ Let ρ be a length-metric on \mathbb{R}^m , which is bi-Lipschitz equivalent to the canonical metric. Assume that every geodesic γ in (\mathbb{R}^d, ρ) is linear (that is, $\gamma(t) = v + w \cdot t$ for some $v, w \in \mathbb{R}^m$). Show that ρ is induced by a norm on \mathbb{R}^m .

Hyperbolic space

A map $f: X \rightarrow Y$ between metric spaces is called a *quasi-isometry* if there is a positive real constant C such that $f(X)$ is a C -net in Y and

$$\frac{1}{C} \cdot |x - y|_X - C \leq |f(x) - f(y)|_Y \leq C \cdot |x - y|_X + C.$$

Note that a quasi-isometry is not assumed to be continuous, for example any map between compact metric spaces is a quasi-isometry.

▮ *Construct a quasi-isometry from the hyperbolic 3-space to a subset of the product of two hyperbolic planes.*

A homeomorphism near quasi-isometry⁺

The quasi-isometry is defined few lines above.

▮ *Let $f: \mathbb{R}^m \rightarrow \mathbb{R}^m$ be a quasi-isometry. Show that there is a (bi-Lipschitz) homeomorphism $h: \mathbb{R}^m \rightarrow \mathbb{R}^m$ on a bounded distance from f ; that is, there is*

$$|f(x) - h(x)| \leq C$$

for any $x \in \mathbb{R}^m$ and a real constant C .

The solution requires a corollary of the theorem proved by Laurence Siebenmann in [117]. It states that if $V_1, V_2 \subset \mathbb{R}^m$ are open and the two embeddings $f_1: V_1 \rightarrow \mathbb{R}^m$ and $f_2: V_2 \rightarrow \mathbb{R}^m$ are sufficiently close to each other on the overlap $U = V_1 \cap V_2$, then there is an embedding f defined on an open set W' which is slightly smaller than $W = V_1 \cup V_2$ and such that f is sufficiently close to each f_1 and f_2 at the points where they are defined.

The bi-Lipschitz version requires an analogous statement in the category of bi-Lipschitz embeddings; it was proved by Dennis Sullivan in [118]. This result can be used to prove that the homeomorphism is bi-Lipschitz.

A family of sets with no section

▮ *Construct a one parameter family of closed sets C_t in \mathbb{S}^1 , $t \in [0, 1]$ which is continuous in the Hausdorff topology, but which does not admit a section; that is, there is no continuous map $c: [0, 1] \rightarrow \mathbb{S}^1$ such that $c(t) \in C_t$ for any t .*

Semisolutions

Non-contracting map. Given any pair of point $x_0, y_0 \in K$, consider two sequences x_0, x_1, \dots and y_0, y_1, \dots such that $x_{n+1} = f(x_n)$ and $y_{n+1} = f(y_n)$ for each n .

Since K is compact, we can choose an increasing sequence of integers n_k such that both sequences $(x_{n_i})_{i=1}^\infty$ and $(y_{n_i})_{i=1}^\infty$ converge. In particular, both of these sequences are Cauchy; that is,

$$|x_{n_i} - x_{n_j}|_K, |y_{n_i} - y_{n_j}|_K \rightarrow 0 \text{ as } \min\{i, j\} \rightarrow \infty.$$

Since f is non-contracting, we get

$$|x_0 - x_{|n_i - n_j|}| \leq |x_{n_i} - x_{n_j}|.$$

It follows that there is a sequence $m_i \rightarrow \infty$ such that

$$(*) \quad x_{m_i} \rightarrow x \text{ and } y_{m_i} \rightarrow y \text{ as } i \rightarrow \infty.$$

Set

$$\ell_n = |x_n - y_n|_K.$$

Since f is non-contracting, (ℓ_n) is a non-decreasing sequence.

By $(*)$, it follows that $\ell_{m_i} \rightarrow \ell_0$ as $m_i \rightarrow \infty$. It follows that (ℓ_n) is a constant sequence.

In particular

$$|x_0 - y_0|_K = \ell_0 = \ell_1 = |f(x_0) - f(y_0)|_K$$

for any pair of points (x_0, y_0) in K . That is, f is distance preserving, in particular injective.

From $(*)$, we also get that $f(K)$ is everywhere dense. Since K is compact $f: K \rightarrow K$ is surjective. Hence the result follows. \square

This is a basic lemma in the introduction to Gromov–Hausdorff distance [see 7.3.30 in 111]. The proof presented here is different, it was given by Travis Morrison, a students in my MASS class at Penn State, Fall 2011.

Horo-compactification. For the first part of problem, take X to be the set of non-negative integers with the metric ρ defined as $\rho(m, n) = m + n$ for $m \neq n$.

Now assume X is geodesic and F_X is not an embedding. Then there is a sequence of points z_1, z_2, \dots and a point z_∞ , such that $f_{z_n} \rightarrow f_{z_\infty}$ in $C(X, \mathbb{R})$ as $n \rightarrow \infty$, while $|z_n - z_\infty|_X > \varepsilon$ for some fixed $\varepsilon > 0$ and all n .

Choose \bar{z}_n on the a geodesic $[z_\infty z_n]$ such that $|z_\infty - z'_n| = \varepsilon$. Note that

$$f_{z_n}(z_\infty) - f_{z_n}(\bar{z}_n) = \varepsilon$$

and

$$f_{z_\infty}(z_\infty) - f_{z_n}(\bar{z}_n) = -\varepsilon$$

for any n . In particular $f_{z_n} \not\rightarrow f_{z_\infty}$ in $C(X, \mathbb{R})$, a contradiction. \square

I learned this problem from Linus Kramer and Alexander Lytchak; the example was also mentioned in the lectures of Anders Karlsson and attributed to Uri Bader [see 2.3 in 119].

Ball and sphere. Make fine burrows in the standard 3-ball which do not change its topology, but at the same time a come sufficiently close to any point in the ball.

Consider the doubling of obtained ball in its boundary. Clearly the obtained space is homeomorphic to \mathbb{S}^3 . Prove that the burrows can be made so that it is sufficiently close to the original ball in the Gromov–Hausdorff metric.

It remains to smooth the obtained space slightly to get a genuine Riemannian metric with needed property. \square

This construction is a stripped version of theorem proved by Steven Ferry and Boris Okunin in [120]. The theorem states that Riemannian metrics on a smooth closed manifold M with $\dim M \geq 3$ can approximate given compact length space X if and only if there is a continuous map $M \rightarrow X$ which is surjective on the fundamental groups.

The two-dimensional case is quite different. There is no sequence of Riemannian metrics on \mathbb{S}^2 which converge in the Gromov–Hausdorff topology to the unit disc. In fact, if X is a Gromov–Hausdorff limit of (\mathbb{S}^2, g_n) , then any point $x_0 \in X$ either admits a neighborhood homeomorphic to \mathbb{R}^2 or it is a cut point; that is $X \setminus \{x_0\}$ is disconnected [see 3.32 in 45].

Macro-dimension. Choose a point $p \in M$, denote by f the distance function from p .

Let us cover M by the connected components of the inverse images $f^{-1}((n-1, n+1))$. Clearly any point in M is covered by at most two such components. It remains to show that each of these components has diameter less than 100.

Assume the contrary; let x and y be two points in such connected component and $|x - y|_M \geq 100$. Connect x to y by a curve τ in the

component. Consider the closed curve σ formed by two geodesics $[px]$, $[py]$ and τ .

Prove that σ can be divided into 4 arcs α , β , γ and δ in such a way that the minimal distance from α to γ as well as the minimal distance from β to δ is at least 10.

Use the last statement to show that σ cannot be shrunk by a disc in its 1-neighborhood; the latter contradicts the assumption. \square

The problem was discussed at a talk by Nikita Zinoviev around 2004.

No short embedding. Consider a chain of disjoint circles c_0, \dots, c_n in \mathbb{R}^3 ; that is, c_i and c_{i-1} are linked for each i .



Assume that \mathbb{R}^3 is equipped with a length-metric ρ , such that the total length of the circles is ℓ and U is an open set containing all the circles c_i . Note that for any short homeomorphism $f: (U, \rho) \rightarrow \mathbb{R}^3$ the distance from $f(c_0)$ to $f(c_n)$ is less than ℓ .

Let us show that the ρ -distance from c_0 to c_n might be much larger than ℓ . Fix a line segment $[ab]$ in \mathbb{R}^3 . Modify the length-metric on \mathbb{R}^3 in arbitrary small neighborhood of $[ab]$ so that there is a chain (c_i) of circles as above, which goes from a to b such that (1) the total length, say ℓ , of (c_i) is arbitrary small, but (2) the obtained metric ρ is arbitrary close to the canonical, say

$$|\rho(x, y) - |x - y|| < \varepsilon$$

for any two points $x, y \in \mathbb{R}^3$ and fixed in advanced small $\varepsilon > 0$. The construction of ρ is done by shrinking the length of each circle and expanding the length in the normal directions to the circles in their small neighborhood. The latter is made in order to make impossible to use the circles c_i as a shortcut; that is, one spends more time to go from one circle to an other than saves on going along the circle.

Set $a_n = (0, \frac{1}{n}, 0)$ and $b_n = (1, \frac{1}{n}, 0)$. Note that the line segments $[a_n b_n]$ are disjoint and converging to $[a_\infty b_\infty]$ where $a_\infty = (0, 0, 0)$ and $b_\infty = (1, 0, 0)$.

Apply the above construction in non-overlapping convex neighborhoods of $[a_n b_n]$ and for a sequences ε_n and ℓ_n which converge to zero very fast.

The obtained length-metric ρ is still close to the canonical, but for any open set U containing $[a_\infty b_\infty]$ the space (U, ρ) does not admit a

short homeomorphism to \mathbb{R}^3 . Indeed, if such homeomorphism h exists, then from the above construction, we get

$$\begin{aligned} |h(a_\infty) - f(b_\infty)| &\leq |h(a_n) - f(b_n)| + \\ &\quad + |h(a_\infty) - f(a_n)| + |h(b_n) - f(b_\infty)| \leq \\ &\leq \ell_n + \frac{2}{n} + 100 \cdot \varepsilon_n. \end{aligned}$$

The right hand side converges to 0 as $n \rightarrow \infty$. Therefore

$$h(a_\infty) = f(b_\infty),$$

a contradiction.

It remains to perform similar construction countably many times so a bad segment as $[a_\infty b_\infty]$ above appears in any open set of \mathbb{R}^3 . \square

The problem is due Dmitri Burago, Sergei Ivanov and David Shoen-thal [see 121].

Sub-Riemannian sphere. Prove that there is a non-decreasing sequence of Riemannian metric tensors $g_0 \leq g_1 \leq \dots$ such that the induced metrics converge to the given sub-Riemannian metrics. The metric g_0 can be assumed to be a metric on round sphere.

Applying the construction as in Nash–Kuiper theorem, one can produce a sequence of smooth embeddings $h_n: \mathbb{S}^m \rightarrow \mathbb{R}^{m+1}$ with the induced metrics g'_n such that $|g'_n - g_n| \rightarrow 0$.

Moreover, assume we assign a positive real number $\varepsilon(h)$ for any smooth embedding $h: \mathbb{S}^m \rightarrow \mathbb{R}^{m+1}$. Then we can assume that

$$|h_{n+1}(x) - h_n(x)| < \varepsilon(h_n)$$

for any $x \in \mathbb{S}^m$ and n .

Show that for a right choice of function $\varepsilon(h_n)$, the sequence h_n converges, say to h_∞ , and the metric induced by h_∞ coincides with the given sub-Riemannian metric. \square

The problem appeared on this list first rediscovered later by Enrico Le Donne in [122]. Similar construction described in the the lecture notes by Allan Yashinski and me [see 123] which is aimed for undergraduate students. Yet [124] is closely relevant.

Length-preserving map. The solution uses Rademacher's theorem, which states that any Lipschitz function $f: \mathbb{R}^n \rightarrow \mathbb{R}$ is differentiable almost everywhere. The Rademacher's theorem appears in [125]. \square

Assume there is a length-preserving map $f: \mathbb{R}^2 \rightarrow \mathbb{R}$.

Note that f is Lipschitz. Therefore by Rademacher's theorem, f is differentiable almost everywhere.

Fix a unit vector u . Prove that, for almost all x , the length of curve $\alpha: t \mapsto x + t \cdot u$, $t \in [0, 1]$ can be expressed as the integral

$$\int_0^1 (d_{\alpha(t)}f)(u) \cdot dt.$$

It follows that $|d_x f(v)| = |v|$ for almost all $x, v \in \mathbb{R}^2$; in particular $d_x f$ is defined and has rank 2 at some point x , a contradiction. \square

The idea above can be also used to solve the following problem.

\diamond Assume ρ is a metric on \mathbb{R}^2 which is induced by a norm. Show that (\mathbb{R}^2, ρ) admits a length-preserving map to \mathbb{R}^3 if and only if (\mathbb{R}^2, ρ) is isometric to the Euclidean plane.

Fixed segment. Note that it is sufficient to show that if

$$f(a) = a \quad \text{and} \quad f(b) = b$$

for some $a, b \in \mathbb{R}^m$, then

$$f\left(\frac{a+b}{2}\right) = \frac{1}{2} \cdot (f(a) + f(b)).$$

(This statement is not trivial since in general metric midpoint of a and b in (\mathbb{R}^m, d) are not defined uniquely.)

Without loss of generality, we can assume that $b + a = 0$.

Set $f_0 = f$. Consider the recursively defined sequence of isometries f_0, f_1, \dots defined recursively

$$f_{n+1}(x) = -f_n^{-1}(-f_n(x)).$$

Note that $f_n(a) = a$ and $f_n(b) = b$ for any n and

$$|f_{n+1}(0)| = 2 \cdot |f_n(0)|.$$

The latter condition implies that if $f(0) \neq 0$, then $|f_n(0)| \rightarrow \infty$ as $n \rightarrow \infty$. On the other hand, since f_n is isometry and $f(a) = a$, we get $|f_n(0)| \leq 2 \cdot |a|$, a contradiction. \square

The problem is a stripped version of Mazur–Ulam theorem proved in [126]; it states that any isometry of (\mathbb{R}^m, d) to itself forms an affine map.

The solution above is the main step in the proof of this theorem given by Jussi Väisälä's in [127].

Pogorelov's construction. Positivity and symmetry of ρ is evident.

The triangle inequality follows since

$$(*) \quad [B(x, \frac{\pi}{2}) \setminus B(y, \frac{\pi}{2})] \cup [B(y, \frac{\pi}{2}) \setminus B(z, \frac{\pi}{2})] \supset B(x, \frac{\pi}{2}) \setminus B(z, \frac{\pi}{2}).$$

Note that we get equality in $(*)$ if and only if y lies on the great circle arc from x to z . Therefore the second statement follows. \square

This construction was given by Aleksei Pogorelov in [128]. It is closely related to the construction given by David Hilbert in [129] which was the motivating example of his 4th problem [see 130].

Straight geodesics. From uniqueness of straight segment between given points in \mathbb{R}^m , it follows that any straight line in \mathbb{R}^m forms a geodesic in (\mathbb{R}^m, ρ) .

Set

$$\|\mathbf{v}\|_{\mathbf{x}} = \rho(\mathbf{x}, (\mathbf{x} + \mathbf{v})).$$

Note that

$$\|\lambda \cdot \mathbf{v}\|_{\mathbf{x}} = |\lambda| \cdot \|\mathbf{v}\|_{\mathbf{x}}$$

for any $\mathbf{x}, \mathbf{v} \in \mathbb{R}^m$ and $\lambda \in \mathbb{R}$.

Prove that

$$\|\lambda \cdot \mathbf{v}\|_{\mathbf{x}} - \|\lambda \cdot \mathbf{v}\|_{\mathbf{x}'} \leq \text{Const} \cdot |\mathbf{x} - \mathbf{x}'|$$

for any $\mathbf{x}, \mathbf{x}', \mathbf{v} \in \mathbb{R}^m$, $\lambda \in \mathbb{R}$ and some fixed $\text{Const} \in \mathbb{R}$.

Passing to the limit as $\lambda \rightarrow \infty$, we get $\|\mathbf{v}\|_{\mathbf{x}}$ does not depend on \mathbf{x} ; hence the result follows. \square

The idea in the proof is due to Thomas Foertsch and Viktor Schroeder [see 131]. A more general statement was proved by Petra Hitzelberger and Alexander Lytchak in [132]. Namely they show that if any pair of points in a geodesic metric space X can be separated by an affine function, then X is isometric to a convex subset a normed vector space.

Hyperbolic space. Note that 2-dimensional hyperbolic space can be viewed as (\mathbb{R}^2, g) , where

$$g(x, y) = \begin{pmatrix} 1 & 0 \\ 0 & e^x \end{pmatrix}.$$

The same way 3-dimensional hyperbolic space can be viewed as (\mathbb{R}^3, h) , where where

$$h(x, y, z) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^x & 0 \\ 0 & 0 & e^x \end{pmatrix}.$$

Prove that the map $\mathbb{R}^3 \rightarrow \mathbb{R}^4$ defined as

$$(x, y, z) \mapsto (x, y, x, z)$$

is a quasi-isometry from (\mathbb{R}^3, h) to its image in $(\mathbb{R}^2, g) \times (\mathbb{R}^2, g)$. \square

In the proof we used that horosphere in the hyperbolic space is isometric to the Euclidean plane. This observation appears already in the book of Nikolai Lobachevsky [see 34 in 133].

A homeomorphism near quasi-isometry.

Let $M \geq 1$ and $A \geq 0$. Define (M, A) -quasi-isometry as a map $f: X \rightarrow Y$ between metric spaces X and Y such that for any $x, y \in X$, we have

$$\frac{1}{M} \cdot |x - y| - A \leq |f(x) - f(y)| \leq M \cdot |x - y| + A$$

and any point in Y lies on the distance at most A from a point in the image $f(X)$.

Note that $(M, 0)$ -quasi-isometry is a $[\frac{1}{M}, M]$ -bi-Lipschitz map. Moreover, if $f_n: \mathbb{R}^m \rightarrow \mathbb{R}^m$ is a $(M, \frac{1}{n})$ -quasi-isometry for each n , then any partial limit of f_n as $n \rightarrow \infty$ is a $[\frac{1}{M}, M]$ -bi-Lipschitz map.

It follows that given $M \geq 1$ and $\varepsilon > 0$ there is $\delta > 0$ such that for any (M, δ) -quasi-isometry $f: \mathbb{R}^m \rightarrow \mathbb{R}^m$ and any $p \in \mathbb{R}^m$ there is an $[\frac{1}{M}, M]$ -bi-Lipschitz map $h: B(p, 1) \rightarrow \mathbb{R}^m$ such that

$$|f(x) - h(x)| < \varepsilon$$

for any $x \in B(p, 1)$.

Applying rescaling, we can get the following equivalent formulation. Given $M \geq 1$, $A \geq 0$ and $\varepsilon > 0$ there is big enough $R > 0$ such that for any (M, A) -quasi-isometry $f: \mathbb{R}^m \rightarrow \mathbb{R}^m$ and any $p \in \mathbb{R}^m$ there is a $[\frac{1}{M}, M]$ -bi-Lipschitz map $h: B(p, R) \rightarrow \mathbb{R}^m$ such that

$$|f(x) - h(x)| < \varepsilon \cdot R$$

for any $x \in B(p, R)$.

Now cover \mathbb{R}^m by balls $B(p_n, R)$, construct a $[\frac{1}{M}, M]$ -bi-Lipschitz map $h_n: B(p_n, R) \rightarrow \mathbb{R}^m$ for each n .

The maps h_n are $2 \cdot \varepsilon \cdot R$ close to each other on the overlaps of their domains of definition. This makes possible to deform slightly each h_n so that they agree on the overlaps. This can be done by Siebenmann's Theorem. If instead you apply Sullivan's theorem, you get a bi-Lipschitz homeomorphism $h: \mathbb{R}^m \rightarrow \mathbb{R}^m$. \square

The problem was suggested by Dmitri Burago.

A family of sets with no section. Identify \mathbb{S}^1 with $[0, 1]/(0 \sim 1)$. Consider one parameter family of Cantor sets K_t formed by all possible sums $\sum_{n=1}^{\infty} a_n \cdot t^n$, where a_i is 0 or 1 and $t \in [0, \frac{1}{2}]$.

Note that $K_{\frac{1}{2}} = \mathbb{S}^1$.

Denote by $\rho_\alpha: \mathbb{S}^1 \rightarrow \mathbb{S}^1$ the rotation by angle α . Set

$$Z_t = \begin{cases} Z_t = \rho_{\frac{1}{1-2^{-t}}} (K_t) & \text{if } t \in [0, \frac{1}{2}), \\ Z_t = \mathbb{S}^1 & \text{if } t = \frac{1}{2}. \end{cases}$$

Prove that the family of sets Z_t is a continuous in the Hausdorff topology and it does not have a section. \square

The problem is suggested by Stephan Stadler.

It is instructive to check that any Hausdorff continuous family of closed sets in \mathbb{R} admits a continuous section.

Chapter 6

Actions and coverings

In this chapter we consider isometric actions and metric coverings. Given a covering $f: \tilde{X} \rightarrow X$ of the length-metric space X , one can consider the induced length-metric on \tilde{X} defining length of curve α in X as the length of the composition $f \circ \alpha$.

Bounded orbit

Recall that a metric space is called *proper* if all its bounded closed sets are compact.

▣ *Let X be a proper metric space and $\iota: X \rightarrow X$ is an isometry. Assume that for some $x \in X$, the sequence $x_n = \iota^n(x)$, $n \in \mathbb{Z}$ has a converging subsequence. Prove that x_n is bounded.*

Semisolution. Note that we can assume that the orbit $x_n = \iota^n(x)$ is dense in X ; otherwise pass to the closure of this orbit. In particular, we can choose a finite number of positive integers values n_1, n_2, \dots, n_k such that the points $x_{n_1}, x_{n_2}, \dots, x_{n_k}$ form a $\frac{1}{10}$ -net in $B(x_0, 10)$, that is, for any $x \in B(x_0, 10)$ there is x_{n_i} such that

$$|x - x_{n_i}| < \frac{1}{10}.$$

Prove that that if $x_m \in B(x_0, 1)$, then $x_{m+n_i} \in B(x_0, 1)$ for some $i \in \{1, \dots, k\}$.

Set $N = \max_i \{n_i\}$. It follows that among any N elements in a row x_{i+1}, \dots, x_{i+N} there is at least one in $B(x_0, 1)$. In particular, N isometric copies of $B(x_0, 1)$ cover whole X . Hence the result follows. \square

The problem is due to Aleksander Całka's [see 134].

Finite action

▮ Show that for any nontrivial continuous action of a finite group on the unit sphere there is an orbit which does not lie in the interior of a hemisphere.

Covers of figure eight

Let us define *figure eight* as the length space which is obtained by gluing together all four ends of two unit segments.



▮ Prove that any compact length spaces K can be presented as a Gromov–Hausdorff limit of a sequence of metric covers

$$(\tilde{\Phi}_n, \tilde{d}/n) \rightarrow (\Phi, d/n),$$

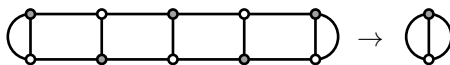
where (Φ, d) denotes the figure eight.

Diameter of m -fold cover*

▮ Let X be a length space and \tilde{X} be a connected m -fold cover of X equipped with the induced intrinsic metric. Show that

$$\text{diam } \tilde{X} \leq m \cdot \text{diam } X.$$

From the diagram below you could guess an example of 5-fold cover with diameter of the total space exactly 5 times diameter of the target.



Symmetric square^o

Let X be a topological space. Note that $X \times X$ admits a natural \mathbb{Z}_2 -action by $(x, y) \mapsto (y, x)$. The quotient space $X \times X / \mathbb{Z}_2$ is called *symmetric square* of X .

▮ Show that symmetric square of any path connected topological space has commutative the fundamental group.

Sierpiński gasket[◦]

To construct Sierpiński gasket, start with a solid equilateral triangle, subdivide it into four smaller congruent equilateral triangles and remove the interior of the central one. Repeat this procedure recursively for each of the remaining solid triangles.



Find the homeomorphism group of the Sierpiński gasket.

Lattices in a Lie group

Let L and M be two discrete subgroups of a connected Lie group G and h be a left invariant metric on G . Equip the groups L and M with the induced left invariant metric from G . Assume $L \backslash G$ and $M \backslash G$ are compact and moreover

$$\text{vol}(L \backslash (G, h)) = \text{vol}(M \backslash (G, h)).$$

Prove that there is a bi-Lipschitz one-to-one mapping (not necessarily a homomorphism)

$$f: L \rightarrow M.$$

Piecewise Euclidean quotient

Note that the quotient of Euclidean space by a finite subgroup is a polyhedral space as it depends on page 93; on the same page you find the definition of piecewise linear homeomorphism.

Let Γ be a finite subgroup of $\text{SO}(m)$. Denote by P the quotient \mathbb{R}^m / Γ equipped with induced polyhedral metric. Assume P admits a piecewise linear homeomorphism to \mathbb{R}^m . Show that Γ is generated by rotations around subspaces of codimension 2.

Subgroups of the free group

Show that every finitely generated subgroup of the free group is an intersection of subgroups of finite index.

Lengths of generators of the fundamental group[◦]

Let M be a compact Riemannian manifold and $p \in M$. Show that the fundamental group $\pi_1(M, p)$ is generated by the homotopy classes of loops with length at most $2 \cdot \text{diam } M$.

Number of generators

▮ Let M be a complete connected Riemannian manifold with non-negative sectional curvature. Show that the minimal number of generators of the fundamental group $\pi_1 M$ can be bounded above in terms of the dimension of M .

Equations in the group[◦]

▮ Assume G is a compact connected Lie group and n is a positive integer. Show that given a collection of elements $g_1, g_2, \dots, g_n \in G$ the equation

$$x \cdot g_1 \cdot x \cdot g_2 \cdots x \cdot g_n = 1$$

has a solution $x \in G$.

Semisolutions

Finite action. Without loss of generality, we may assume that the action is generated by a nontrivial homeomorphism

$$a: \mathbb{S}^m \rightarrow \mathbb{S}^m$$

and $a^p = \text{id}_{\mathbb{S}^m}$ for some prime p .

Assume that any a -orbit lies in an open hemisphere. Then

$$h(x) = \sum_{n=1}^p a^n \cdot x \neq 0$$

for any $x \in \mathbb{S}^m$.

Consider the map $f: \mathbb{S}^m \rightarrow \mathbb{S}^m$ defined as $f(x) = \frac{h(x)}{|h(x)|}$. Note that

- (i) if $a(x) = x$, then $f(x) = x$;
- (ii) $f(x) = f \circ a(x)$ for any $x \in \mathbb{S}^m$.

Prove that f is homotopic to the identity; in particular

$$(*) \quad \deg f = 1.$$

Fix $x \in \mathbb{S}^m$ such that $a(x) \neq x$. Note that a acts without fixed points on the inverse image $W = f^{-1}(V)$ of a small open neighborhood $V \ni x$. Therefore the quotient map $\theta: W \rightarrow W' = W/\mathbb{Z}_p$ is a p -fold covering. From (ii), the restriction $f|_W$ factors through θ ; that is there is $f': W' \rightarrow V$ such that $f|_W = f' \circ \theta$.

Assume $p \neq 2$. Show that f' and θ have well defined degrees and

$$\deg f \equiv \deg \theta \cdot \deg f' \pmod{p}$$

Since θ is a p -fold covering, we have $\deg \theta \equiv 0 \pmod{p}$. Therefore

$$(**) \quad \deg f \equiv 0 \pmod{p}.$$

Finally observe that $(*)$ contradicts $(**)$.

In the case $p = 2$ the same proof works, but the degrees have to be defined only modulo 2. \square

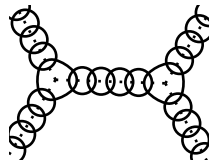
Along the same lines one can get a lower bound for the maximal diameter of orbit for any nontrivial actions of finite groups on a Riemannian manifold.

Applying the problem to a conjugate action, one gets that if a fixed point set of a finite group action $F \curvearrowright \mathbb{S}^m$ has nonempty interior, then the action is trivial. The same holds for any connected manifold; it was proved by Max Newman in [135].

The Newman's theorem was used by Deane Montgomery in [136] to show that *if h is a homeomorphism of a connected manifold M such that each h -orbit is finite, then $h^n = \text{id}_M$ for some positive integer n .*

Covers of figure eight. First show that any compact metric space can be presented as a limit of a sequence of finite metric graphs Γ_n . Moreover, show that one can assume each vertex of Γ_n has degree 3 and the length of each edge in Γ_n is multiple of $\frac{1}{n}$.

It remains to approximate Γ_n by finite coverings of $(\Phi, d/n)$. Guess this part from the following picture; it shows the needed approximation of the dotted graph. \square



The same idea works if instead of figure eight, we have any compact length space X which admits a map $X \rightarrow \Phi$ which is surjective on fundamental groups. Such spaces X can be found among compact hyperbolic manifolds of any dimension ≥ 2 . All this due to Vedrin Sahovic [see 137].

A similar idea was used later to show that any group can appear as a fundamental group of underlying space of 3-dimensional hyperbolic orbifold [see 138].

Diameter of m -fold cover. Fix points $\tilde{p}, \tilde{q} \in \tilde{M}$. Let $\tilde{\gamma}: [0, 1] \rightarrow \tilde{M}$ be a minimizing geodesic from \tilde{p} to \tilde{q} .

We need to show that

$$\text{length } \tilde{\gamma} \leq m \cdot \text{diam}(M).$$

Suppose the contrary.

Denote by p, q and γ the projections to M of \tilde{p}, \tilde{q} and $\tilde{\gamma}$. Represent γ as joint of m paths of equal length,

$$\gamma = \gamma_1 * \dots * \gamma_m,$$

so

$$\text{length}(\gamma_i) = \text{length}(\gamma)/m > \text{diam}(M).$$

Let σ_i be a minimizing geodesic in M connecting the endpoints of γ_i . Note that

$$\text{length } \sigma_i \leq \text{diam } M < \text{length } \gamma_i.$$

Consider $m+1$ paths $\alpha_0, \dots, \alpha_m$ defined as

$$\alpha_i = \sigma_1 * \dots * \sigma_i * \gamma_{i+1} * \dots * \gamma_m.$$

Consider their liftings $\tilde{\alpha}_0, \dots, \tilde{\alpha}_m$ with \tilde{q} as the endpoint. Note that two curves, say α_i and α_j for $i < j$, have the same starting point in \tilde{M} .

Consider the path

$$\beta = \gamma_1 * \dots * \gamma_i * \sigma_{i+1} * \dots * \sigma_j * \gamma_{j+1} * \dots * \gamma_m.$$

Prove that there is lift $\tilde{\beta}$ of β which connects \tilde{p} to \tilde{q} in \tilde{M} . Clearly $\text{length } \beta < \text{length } \gamma$, a contradiction. \square

The question was asked by Alexander Nabutovsky and answered by Sergei Ivanov [see 139].

Symmetric square. Let $\Gamma = \pi_1 X$ and $\Delta = \pi_1((X \times X)/\mathbb{Z}_2)$. Consider the homomorphism $\varphi: \Gamma \times \Gamma \rightarrow \Delta$ induced by the projection $X \times X \rightarrow (X \times X)/\mathbb{Z}_2$.

Prove that the restrictions $\varphi|_{\Gamma \times \{1\}}$ and $\varphi|_{\{1\} \times \Gamma}$ are onto.

It remains to note that

$$\varphi(\alpha, 1)\varphi(1, \beta) = \varphi(1, \beta)\varphi(\alpha, 1)$$

for any α and β in Γ . \square

The problem was suggested by Rostislav Matveyev.

Sierpiński gasket. Denote the Sierpiński gasket by Δ .

Let us show that any homeomorphism of Δ is also its isometry. Therefore the group homeomorphisms is the symmetric group S_3 .

Let $\{x, y, z\}$ be a 3-point set in Δ such that $\Delta \setminus \{x, y, z\}$ has 3 connected components. Prove that there is unique choice for the set $\{x, y, z\}$ and it is formed by the midpoints of its big sides.

It follows that any homeomorphism of Δ permutes the set $\{x, y, z\}$.

A similar argument shows that this permutation uniquely describes the homeomorphism. \square

The problem was suggested by Bruce Kliener. The homeomorphism group of Sierpiński carpet is much bigger, it is instructive to describe this group.

Lattices in a Lie group. Denote by V_ℓ and W_m the Voronoi domain of for each $\ell \in L$ and $m \in M$ correspondingly; that is,

$$V_\ell = \{ g \in G \mid |g - \ell|_G \leq |g - \ell'| \text{ for any } \ell' \in L \}$$

$$W_m = \{ g \in G \mid |g - m|_G \leq |g - m'| \text{ for any } m' \in M \}$$

Note that for any $\ell \in L$ and $m \in M$ we have

$$\begin{aligned} \text{vol } V_\ell &= \text{vol}(L \setminus (G, h)) = \\ (*) \quad &= \text{vol}(M \setminus (G, h)) = \\ &= \text{vol } W_m. \end{aligned}$$

Consider the bipartite graph Γ with vertices formed by the elements of L and M such that $\ell \in L$ is adjacent to $m \in M$ if and only if $V_\ell \cap W_m \neq \emptyset$.

By $(*)$ the graph Γ satisfies the condition in the marriage theorem — any subset in L has at least that many neighbors in M and the other way around. Therefore there is a bijection $f: L \rightarrow M$ such that

$$V_\ell \cap W_{f(\ell)} \neq \emptyset$$

for any $\ell \in L$.

It remains to notice that f is bi-Lipschitz. \square

The problem is due to Dmitri Burago and Bruce Kleiner [see 140]. For a finitely generated group G it is not known if G and $G \times \mathbb{Z}_2$ can fail to be bi-Lipschitz. (The groups are assumed to be equipped with word metric.)

Piecewise Euclidean quotient. Note that the group Γ serves as holonomy group of the quotient space $P = \mathbb{R}^m / \Gamma$ with the induced polyhedral metric. More precisely, one can identify \mathbb{R}^m with the tangent space of a regular point x_0 of P in such a way that for any $\gamma \in \Gamma$ there is a loop ℓ in P which pass only through regular points and has the holonomy γ .

Fix $\gamma \in \Gamma$. Let ℓ be the corresponding loop. Since P is simply connected, we can shrink ℓ by a disc. By general position argument

we can assume that the disc only pass through simplices of codimension 0, 1 and 2 and intersect the simplices of codimension 2 transversely.

In other words, ℓ can be presented as a product of loops such that each loop goes around a single simplex of codimension 2 and comes back. The holonomy for each of these loops is a rotation around a hyperplane. Hence the result follows. \square

The converse to the problem also holds; it was proved by Christian Lange in [141], his proof based earlier results of Marina Mikhailova [see 142].

Note that the cone over spherical suspension over Poincaré sphere is homeomorphic to \mathbb{R}^5 and it is quotient of \mathbb{R}^5 by a finite subgroup of $SO(5)$. Therefore, if one exchanges “piecewise linear homeomorphism” to “homeomorphism” in the formulation, then the answer is different; a complete classification of such actions was also obtained in [141].

Subgroups of free group. Let F be a free group; note that we can assume that F has finite number, say m , generators.

Fix a finitely generated subgroup G of free group F .

Let W be the wedge sum of m circles, so $\pi_1(W, p) = F$. Equip W with the length-metric such that each circle has unit length.

Pass to the metric cover \tilde{W} of W such that $\pi_1(\tilde{W}, \tilde{p}) = G$ for a lift \tilde{p} of p .

Fix sufficiently large integer n and consider doubling of the closed ball $\bar{B}(\tilde{p}, n + \frac{1}{2})$ in its boundary. Let us denote the obtained doubling by Z_n and set $G_n = \pi(Z_n, \tilde{p})$.

Prove that Z_n is a metric covering of W ; it makes possible to consider G_n as a subgroup of F . By construction, Z_n is compact; therefore G_n has finite order in F .

It remains to show that that

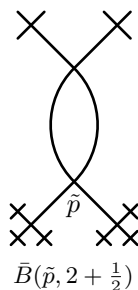
$$G = \bigcap_{n > k} G_n,$$

where k is the maximal length of word in the generating set of G . \square

Originally the problem was solved by Marshall Hall in [143]. The proof presented here is close to the solution of John Stallings in [144]; see also [145].

The same idea can be used to solve many other problems; here are some examples.

- ◇ Show that subgroups of free groups are free.
- ◇ Show that two elements of the free groups u and v commute if and only if they are both powers of the some element w .



Lengths of generators of the fundamental group. Choose a length minimizing loop γ which represents a given element $a \in \pi_1 M$.

Fix $\varepsilon > 0$. Represent γ as a joint

$$\gamma = \gamma_1 * \dots * \gamma_n$$

of paths with length $\gamma_i < \varepsilon$ for each i .

Denote by $p = p_0, p_1, \dots, p_n = p$ the endpoints of these arcs. Connect p to p_i by a minimizing geodesic σ_i . Note that γ is homotopic to a product of loops

$$\alpha_i = \sigma_{i-1} * \gamma_i * \sigma_{i-1}$$

and length $\alpha_i < 2 \cdot \text{diam } M + \varepsilon$ for each i .

It remains to show that for sufficiently small $\varepsilon > 0$ any loop with length less than $2 \cdot \text{diam } M + \varepsilon$ is homotopic to a loop with length at most $2 \cdot \text{diam } M$. \square

The statement is due to Mikhael Gromov [Prop. 3.22 in 45].

Number of generators. Consider universal Riemannian cover \tilde{M} of M . Note that \tilde{M} is non-negatively curved and $\pi_1 M$ acts by isometries on \tilde{M} .

Fix $p \in \tilde{M}$. Given $a \in \pi_1 M$, set

$$|a| = |p - a \cdot p|_{\tilde{M}}.$$

Construct a sequence of elements $a_1, a_2, \dots \in \pi_1 M$ the following way:

- (i) Choose $a_1 \in \pi_1 M$ so that $|a_1|$ takes the minimal value.
- (ii) Choose $a_2 \in \pi_1 M \setminus \langle a_1 \rangle$ so that $|a_2|$ takes the minimal value.
- (iii) Choose $a_3 \in \pi_1 M \setminus \langle a_1, a_2 \rangle$ so that $|a_3|$ takes the minimal value.
- (iv) and so on.

Note that the sequence terminates at n -th step if (a_1, \dots, a_n) forms a generating system. By construction, we have

$$|a_j \cdot a_i^{-1}| \geq |a_j| \geq |a_i|$$

for any $j > i$. Set $p_i = a_i \cdot p$. Note that

$$\begin{aligned} |p_j - p_i|_{\tilde{M}} &= |a_j \cdot a_i^{-1}| \geq \\ &\geq |a_j| = \\ &= |p_j - p|_{\tilde{M}} \geq \\ &\geq |a_i| = \\ &= |p_i - p|_{\tilde{M}}. \end{aligned}$$

By Toponogov comparison theorem we get

$$\angle[p_{p_j}^{p_i}] \geq \frac{\pi}{3}.$$

That is, the directions from p to all p_i lie on the angle at least $\frac{\pi}{3}$ from each other.

Therefore the number of p_i can be bounded in terms of the dimension of M . Hence the result follows. \square

This construction introduced by Mikhael Gromov in his paper on almost flat manifolds [see 54].

Equations in the group. Set

$$f(x) = x \cdot g_1 \cdot x \cdot g_2 \cdots x \cdot g_n.$$

Note that f is homotopic to the map

$$h: x \mapsto x^n.$$

It remains to note that degree of h is not zero. \square

The idea of solution is due to Murray Gerstenhaber and Oscar Rothaus [see 146]. In fact $\deg h = n^k$, where k is the rank of G ; it was proved by Heinz Hopf in [147].

Chapter 7

Topology

In this chapter we consider geometrical problems with strong topological flavor. A typical introductory course in topology, say [148], contains all the necessary material.

Isotropy

Recall that an isotopy is a continuous one parameter family of embeddings.

▮ Let K_1 and K_2 be homeomorphic compact subsets of the coordinate subspace \mathbb{R}^m in $\mathbb{R}^{2 \cdot m}$. Show that there is a homeomorphism

$$h: \mathbb{R}^{2 \cdot m} \rightarrow \mathbb{R}^{2 \cdot m}$$

such that $K_2 = h(K_1)$. Moreover, h can be chosen to be isotopic to the identity map.

Semisolution. Fix a homeomorphism $\varphi: K_1 \rightarrow K_2$.

By Tietze extension theorem, the homeomorphisms $\varphi: K_1 \rightarrow K_2$ and $\varphi^{-1}: K_2 \rightarrow K_1$ can be extended to a continuous maps, say $f: \mathbb{R}^m \rightarrow \mathbb{R}^m$ and $g: \mathbb{R}^m \rightarrow \mathbb{R}^m$ correspondingly.

Consider the homeomorphisms $h_1, h_2, h_3: \mathbb{R}^m \times \mathbb{R}^m \rightarrow \mathbb{R}^m \times \mathbb{R}^m$ defined the following way

$$h_1(x, y) = (x, y + f(x)),$$

$$h_2(x, y) = (x - g(y), y),$$

$$h_3(x, y) = (y, -x).$$

It remains to prove that each homeomorphism h_i is isotopic to the identity map and we have $K_2 = h(K_1)$ for

$$h = h_3 \circ h_2 \circ h_1.$$

□

The problem is due to Victor Klee [see 149]. The problem “Monotonic homotopy” on page 103 is closely related.

Immersed disks

Two immersions $f_1, f_2: D \looparrowright \mathbb{R}^2$ are called *essentially different* if there is no diffeomorphism $h: D \rightarrow D$ such that $f_1 = f_2 \circ h$.

☞ *Construct two essentially different smooth immersions of the disk into the plane which coincide near the boundary.*

Positive Dehn twist

Let Σ be a surface and $\gamma: \mathbb{R}/\mathbb{Z} \rightarrow \Sigma$ be non-contractible closed simple curve. Let U_γ be a neighborhood of γ which admits a homeomorphism $h: U_\gamma \rightarrow \mathbb{R}/\mathbb{Z} \times (0, 1)$. *Dehn twist* along γ is a homeomorphism $f: \Sigma \rightarrow \Sigma$ which is identity outside of U_γ and such that

$$h \circ f \circ h^{-1}: (x, y) \mapsto (x + y, y).$$

If Σ is oriented and h is orientation preserving, then the Dehn twist described above is called *positive*.

☞ *Let Σ be an oriented surface with non empty boundary. Prove that any composition of positive Dehn twists of Σ is not homotopic to identity rel. boundary.*

Function with no critical points

☞ *Given an integer $m \geq 2$, construct a smooth function $f: \mathbb{R}^m \rightarrow \mathbb{R}$ with no critical points in the unit ball B^m such that the restriction $f|_{B^m}$ does not factor through a linear function; that is, $f|_{B^m}$ cannot be presented as a composition $\ell \circ \varphi$, where $\ell: \mathbb{R}^m \rightarrow \mathbb{R}$ is a linear function and $\varphi: B^m \rightarrow \mathbb{R}^m$ is a smooth embedding.*

Conic neighborhood

Let p be a point in a topological space X . We say that an open neighborhood $U \ni p$ is *conic* if there is a homeomorphism from a cone to U which sends its vertex to p .

☞ *Show that any two conic neighborhoods of one point are homeomorphic to each other.*

Unknots

▮ Prove that the set of smooth embeddings $f: \mathbb{S}^1 \rightarrow \mathbb{R}^3$ equipped with the C^0 -topology forms a connected space.

Stabilization

▮ Construct two compact subsets $K_1, K_2 \subset \mathbb{R}^2$ such that K_1 is not homeomorphic to K_2 , but $K_1 \times [0, 1]$ is homeomorphic to $K_2 \times [0, 1]$.

Homeomorphism of cube

▮ Let \square^m be a cube in \mathbb{R}^m . Assume that a homeomorphism $h: \square^m \rightarrow \square^m$ sends each face of \square^m to itself. Extend h to a homeomorphism $f: \mathbb{R}^m \rightarrow \mathbb{R}^m$ which coincides with the identity map outside of a bounded set.

Finite topological space[◦]

▮ Given a finite topological space F construct a finite simplicial complex K which admits a weak homotopy equivalence $K \rightarrow F$.

Dense homeomorphism[◦]

▮ Let \mathcal{H} be the set of all homeomorphisms $\mathbb{S}^2 \rightarrow \mathbb{S}^2$ equipped with the C^0 -metric. Show that there is a homeomorphism $h \in \mathcal{H}$ such that its conjugations $a \circ h \circ a^{-1}$ for all $a \in \mathcal{H}$ form a dense set in \mathcal{H} .

Simple path[◦]

▮ Let p and q be distinct points in Hausdorff topological space X . Assume p and q are jointed by a path. Show that they can be jointed by a simple path; that is there is an injective continuous map $\beta: [0, 1] \rightarrow X$ such that $\beta(0) = p$ and $\beta(1) = q$.

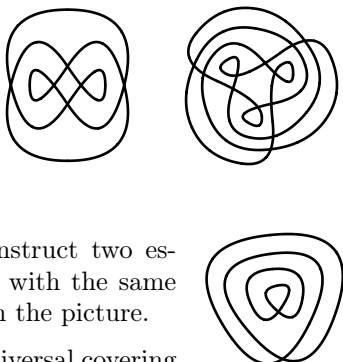
Semisolutions

Immersed disks. Both circles on the picture bound essentially different discs.

It is a good exercise to count the discs in these examples. (The answers are 2 and 5 correspondingly.) \square

The first example is generally attributed to John Milnor. The second example was given by Daniel Bennequin in [150].

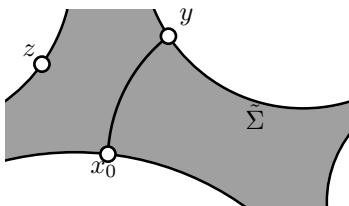
An easier problem would be to construct two essentially different immersions of annuli with the same boundary curves; a solution is shown on the picture.



Positive Dehn twist. Consider the universal covering $\tilde{\Sigma} \rightarrow \Sigma$. The surface $\tilde{\Sigma}$ comes with the orientation induced from Σ .

Note that we may assume that $\tilde{\Sigma}$ has infinite number of boundary components.

Fix a point x_0 on the boundary of $\tilde{\Sigma}$. Given other points y and z we will write $y \prec z$ if z lies on the left side from one (and therefore any) simple curve from x_0 to y in $\tilde{\Sigma}$. Note that \prec defines a linear order on $\partial\tilde{\Sigma} \setminus \{x_0\}$. We will write $y \preceq z$ if $y \prec z$ or $y = z$.



Note that any homeomorphism $h: \Sigma \rightarrow \Sigma$ which is identity on the boundary lifts to unique homeomorphism $\tilde{h}: \tilde{\Sigma} \rightarrow \tilde{\Sigma}$ in such a way that $\tilde{h}(x_0) = x_0$.

Assume h is positive Dehn twist. Show that $y \preceq \tilde{h}(y)$ for any $y \in \partial\tilde{\Sigma} \setminus \{x_0\}$ and there is a point $y_0 \in \partial\tilde{\Sigma} \setminus \{x_0\}$ such that $y_0 \prec \tilde{h}(y_0)$.

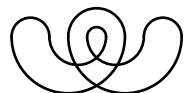
Note that the latter property is a homotopy invariant and it survives under compositions of maps. Hence the statement follows.

Comments. The problem was suggested by Rostislav Matveyev.

Function with no critical points. Construct an immersion $\psi: B^m \looparrowright \mathbb{R}^m$ such that

$$\ell \circ \varphi \neq \ell \circ \psi$$

for any embedding $\varphi: B^m \rightarrow \mathbb{R}^m$. (The two-dimensional case can be guessed from the picture.)



It remains to note that the composition $f = \ell \circ \psi$ has no critical points. \square

The problem was suggested by Petr Pushkar.

Conic neighborhood. Let V and W be two conic neighborhoods of p . Without loss of generality, we may assume that the closure of V lies in W .

We will need to construct a sequence of embeddings $f_n: V \rightarrow W$ such that

- (i) For any compact set $K \subset V$ there is a positive integer $n = n_K$ such that $f_n(k) = f_m(k)$ for any $k \in K$ and $m \geq n$.
- (ii) For any point $w \in W$ there is a point $v \in V$ such that $f_n(v) = w$ for all large n .

Note that once such sequence is constructed, $f: V \rightarrow W$ defined as $f(v) = f_n(v)$ for all large values of n gives the needed homeomorphism.

The sequence f_n can be constructed recursively, setting

$$f_{n+1} = \Psi_n \circ f_n \circ \Phi_n,$$

where $\Phi_n: V \rightarrow V$ and $\Psi_n: W \rightarrow W$ are homeomorphisms of the form

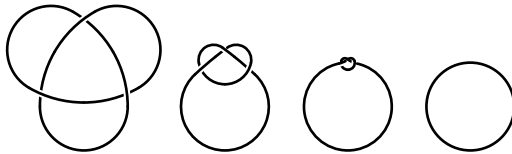
$$\Phi_n(x) = \varphi_n(x) \cdot x \quad \Psi_n(x) = \psi_n(x) \cdot x,$$

where $\varphi_n: V \rightarrow \mathbb{R}_+$, $\psi_n: W \rightarrow \mathbb{R}_+$ are suitable continuous functions and “ \cdot ” denotes the “multiplication” in the cone structures of V and W correspondingly. \square

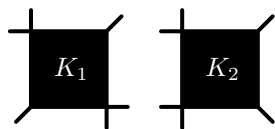
The problem is due to Kyung Whan Kwun [see 151].

Note that for two cones $\text{Cone}(\Sigma_1)$ and $\text{Cone}(\Sigma_2)$ might be homeomorphic while Σ_1 and Σ_2 are not.

Unknots. Observe that it is possible to draw tight arbitrary knot while keeping it smoothly embedded all the time including the last moment. \square



This problem was suggested by Greg Kuperberg [see 152].



Simple stabilization. The example can be guessed from the diagram. \square

I learned this problem in my analysis class taught by Maria Goluzina.

Homeomorphism of cube. Let us extend the homeomorphism h to whole \mathbb{R}^m by reflecting the cube in its facets. We get a homeomorphism say $\tilde{h}: \mathbb{R}^m \rightarrow \mathbb{R}^m$ such that $\tilde{h}(x) = h(x)$ for any $x \in \square^m$ and

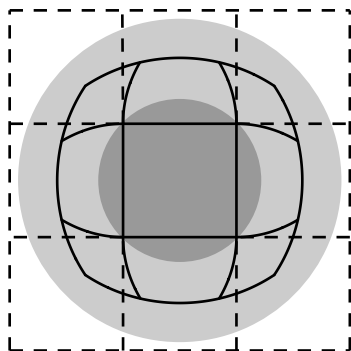
$$\tilde{h} \circ \gamma = \gamma \circ \tilde{h}$$

for any motion $\gamma: \mathbb{R}^m \rightarrow \mathbb{R}^m$ in the group generated by the reflections in the facets of the cube.

Without loss of generality, we may assume that the cube \square^m is inscribed in the unit sphere centered at the origin of \mathbb{R}^m . In this case \tilde{h} has *displacement* at most 2; that is,

$$|\tilde{h}(x) - x| \leq 2$$

for any $x \in \mathbb{R}^m$.



Fix a smooth increasing concave function $\varphi: \mathbb{R} \rightarrow \mathbb{R}$ such that $\varphi(r) = r$ for any $r \leq 1$ and $\sup_r \varphi(r) = 2$.

Consider \mathbb{R}^m with polar coordinates (u, r) , where $u \in \mathbb{S}^{m-1}$ and $r \geq 0$. Let $\Phi: \mathbb{R}^m \rightarrow \mathbb{R}^m$ is defined by $\Phi(u, r) = (u, \varphi(r))$.

Set

$$f(x) = \begin{cases} x & \text{if } |x| \geq 2 \\ \Phi \circ \tilde{h} \circ \Phi^{-1}(x) & \text{if } |x| < 2 \end{cases}$$

Prove that $f: \mathbb{R}^m \rightarrow \mathbb{R}^m$ is a solution. \square

The problem is a stripped from the proof of Robion Kirby in [153]. The condition that face is mapped to face can be removed and instead of homeomorphism one can take an embedding which is close enough to the identity.

An interesting twist to this idea was given by Dennis Sullivan in [118]. Instead of the discrete group of motions of Euclidean space, he use a discrete group of motions of hyperbolic space in the Poincare model. Say, assume we repeat the same argument if instead of cube we have a Coxeter polytope in the hyperbolic space. Then the constructed map coincides with the identity on the absolute and therefore the last “shrinking” step in the proof above is not needed. Moreover, if the

original homeomorphism is bi-Lipschitz, then the construction also produce a bi-Lipschitz homeomorphism; this is the advantage.

Finite topological space. Given a point $p \in F$, denote by O_p the minimal open set in F containing p . Note that we can assume that F connected and is T_0 ; that is $O_p = O_q$ if and only if $p = q$.

Let us write $p \preccurlyeq q$ if $O_p \subset O_q$. The relation \preccurlyeq is a partial order on F .

Let us construct a simplicial complex K by taking F as the set of its vertices and saying that a collection of vertices form a simplex if they can form an increasing sequence with respect to \preccurlyeq .

Given $k \in K$, consider the minimal simplex $(f_0, \dots, f_m) \ni k$; we can assume that $f_0 \preccurlyeq \dots \preccurlyeq f_m$. Set $h: k \mapsto f_0$; it defines a map $K \rightarrow F$.

It remains to check that h is continuous and induces an isomorphism of all the homotopy groups. \square

In a similar fashion, one can construct a finite topological space F for given simplicial complex K such that there is a weak homotopy equivalence $K \rightarrow F$. Both constructions are due to Pavel Alexandrov, [see 154, 155].

Dense homeomorphism. Note that there is countable set of homeomorphisms h_1, h_2, \dots which is dense in \mathcal{H} such that each h_n fix all the points outside an open round disc, say D_n .

Choose a countable disjoint collection of round discs D'_n and consider the homeomorphism $h: \mathbb{S}^2 \rightarrow \mathbb{S}^2$ which fix all the points outside of $\bigcup_n D'_n$ and for each n , the restriction $h|_{D'_n}$ is conjugate to $h_n|_{D_n}$.

Show that h solves the problem. \square

The problem was mentioned by Frederic Le Rox [see 156].

Simple path. Let α be a path joining p to q .

Passing to a subinterval if necessary, we can assume that $\alpha(t) \neq p, q$ for $t \neq 0, 1$.

An open set in $[0, 1]$ will be called *suitable* if for any connected component (a, b) of Ω we have $\alpha(a) = \alpha(b)$. Show that there is a maximal suitable open set Ω ; that Ω is suitable and it is not a subset of any other suitable set.

Define $\beta(t) = \alpha(a)$ for any t in a connected component $(a, b) \subset \Omega$.

It remains to reparametrize β to make it injective. \square

The problem inspired by a Lemma 7.13 proved by Alexander Lytchak and Stefan Wenger in [157]

A more involved solution goes the following way: Note that one can assume that X coincides with the image of α . In particular it is connected, locally connected and compact.

Any such space admits a length metric. This statement was conjectured by Karl Menger in [158] and proved independently by R. H. Bing [see 159, 160] and Edwin Moise [see 161].

It remains to consider a geodesic path from p to q .

Chapter 8

Piecewise linear geometry

In this chapter we consider triangulations and polyhedral spaces as defined below.

A *polyhedral space* is complete length space which admits a locally finite triangulation such that each simplex is isometric to a simplex in a Euclidean space. By *triangulation* of polyhedral space we always understand triangulation as above.

A point in a polyhedral space is called *regular* if it has a neighborhood isometric to an open set in a Euclidean space; otherwise it called *singular*.

If one exchange Euclidean space to the unit sphere or hyperbolic space, one gets definition of *spherical* and correspondingly *hyperbolic polyhedral spaces*.

The term *piecewise* typically mean that there is a triangulation with some property on each triangle. In the following two examples we assume that P and Q be polyhedral spaces.

A map $f: P \rightarrow Q$ is called *piecewise distance preserving* if there is a triangulation \mathcal{T} of P such that at any simplex $\Delta \in \mathcal{T}$ the restriction $f|_{\Delta}$ is distance preserving.

A map $h: P \rightarrow Q$ is called *piecewise linear* if both spaces P and Q admit triangulations such that each simplex of P is mapped to a simplex of Q by an affine map. In particular, a *piecewise linear homeomorphism* is a piecewise linear map which is a homeomorphism.

Spherical arm lemma

☞ Let $A = a_1a_2 \dots a_n$ and $B = b_1b_2 \dots b_n$ be two simple spherical polygons with equal corresponding sides. Assume A lies in a hemisphere and $\angle a_i \geq \angle b_i$ for each i . Show that A is congruent to B .

Semisolution. Let us cut the polygon A from the sphere and glue instead the polygon B . Denote by Σ the obtained spherical polyhedral space. Note that

- ◊ Σ is homeomorphic \mathbb{S}^2 .
- ◊ Σ has curvature ≥ 1 in the sense of Alexandrov; that is, the total angle around each singular point is less than 2π .
- ◊ All the singular points of Σ lie outside of an isometric copy of a hemisphere $\mathbb{S}_+^2 \subset \Sigma$

It is sufficient to show that Σ is isometric to the standard sphere. Assume the contrary. If n denotes be the number of singular points in Σ , it means that $n > 0$.

We will arrive to a contradiction applying induction on n . The base case $n = 1$ is trivial; that is, Σ cannot have single singular point.

Now assume Σ has $n > 1$ singular points. Choose two singular points p, q , cut Σ along a geodesic $[pq]$ and patch the hole so that the obtained new polyhedron Σ' has curvature ≥ 1 . The patch is obtained by doubling a spherical triangle in two sides. For the right choice of the triangle, the points p and q become regular in Σ' and exactly one new singular point appears in the patch.

This way, constructed a spherical polyhedral space Σ' with $n - 1$ singular points which satisfy the same conditions as Σ

By induction hypothesis Σ' does not exist. Hence the result follow. \square

The problem is due to Victor Zalgaller [see 162]; the result of Victor Toponogov in [163] is closely related. The patch construction above was introduced by Aleksandr Alexandrov in his proof of convex embeddability of polyhedrons; the earliest reference we have found is [164, VI, §7].

Here is an alternative end of proof given in [95]: By Alexandrov embedding theorem, Σ is isometric to the surface of convex polyhedron P in the unit 3-dimensional sphere \mathbb{S}^3 . The center of hemisphere has to lie in a facet, say F of P . It remains to note that F contains the equator and therefore P has to be hemisphere in \mathbb{S}^3 or intersection of two hemispheres. In both cases its surface is isometric to \mathbb{S}^2 .

Triangulation of 3-sphere

\boxtimes Construct a triangulation of \mathbb{S}^3 such with 100 vertices such that any two vertices are connected by an edge.

Folding problem

▮ Let P be a compact 2-dimensional polyhedral space. Construct a piecewise distance preserving map $f: P \rightarrow \mathbb{R}^2$.

Piecewise linear extension

We say that a map $f: X \rightarrow Y$ between metric spaces is *short* if it is the same as distance non-expanding; that is

$$|f(x) - f(x')|_Y \leq |x - x'|_X$$

for any $x, x' \in X$.

▮ Prove that any short map from a finite subset $F \subset \mathbb{R}^2$ to \mathbb{R}^2 can be extended to a piecewise distance preserving map $\mathbb{R}^2 \rightarrow \mathbb{R}^2$.

Closed polyhedral surface

▮ Construct a closed polyhedral surface in \mathbb{R}^3 with nonpositive curvature; that is the total angle around each vertex is at least 2π .

Minimal polyhedron

By a polyhedral disc in \mathbb{R}^3 we understand a triangulation of a plane polygon with a map in \mathbb{R}^3 which is affine on each triangle. The area of the polyhedral disc is defined as the sum of areas of the images of the triangles in the triangulation.

▮ Consider the class of polyhedral discs glued from n triangles in \mathbb{R}^3 with fixed broken line as the boundary. Let Σ_n be a disc of minimal area in this class. Show that Σ_n is saddle; that is a plane can not cut all the edges comming from one of the interior vertices of Σ_n .

Coherent triangulation^o

A triangulation of a convex polygon is called coherent if there is a convex function which is linear on each triangle and changes the gradient if you come through any edge of the triangulation.

▮ Find a non-coherent triangulation of a triangle.

Characterization of polytope

▮ Let P be a compact subset of the Euclidean space. Assume for every point $x \in P$ there is a cone K_x with a tip at x and $\varepsilon > 0$ such that

$$B(x, \varepsilon) \cap P = B(x, \varepsilon) \cap K_x.$$

Show that P is a polytope; that is, P is a union of finite collection of simplices.

A sphere with one edge*

▮ Given a spherical polyhedral space P , denote by P_s the subset of its singular points.

Construct spherical polyhedral space P which is homeomorphic to \mathbb{S}^3 and such that P_s is formed by a knotted circle. Show that in such an example the total length of P_s can be arbitrary large and the angle around P_s can be made strictly less than 2π .

Triangulation of a torus

▮ Show that the torus does not admit a triangulation such that one vertex has 5 edges, one has 7 edges and all other vertexes have 6 edges.

No simple geodesics^o

▮ Construct a convex polyhedron P whose surface does not have a closed simple geodesic.

Semisolutions

Triangulation of 3-sphere. Choose 100 distinct points $x_1, x_2, \dots, \dots, x_{100}$ on the moment curve

$$\gamma: t \mapsto (t, t^2, t^3, t^4)$$

in \mathbb{R}^4 . Let P be the convex hull of $\{x_1, x_2, \dots, x_{100}\}$.

Prove that for any two points x_i and x_j there is a hyperplane H in \mathbb{R}^4 which pass through x_i and x_j and leaves γ on one side. The latter statement implies that any two vertices x_i and x_j of P are connected by an edge.

The statement follows since the surface of P is homeomorphic to \mathbb{S}^2 . \square

The polyhedron P above is an example of so called *cyclic polytopes*.

Folding problem. Given a triangulation of P consider the Voronoi domain for each vertex. Prove that the triangulation can be subdivided if necessary so that Voronoi domain of each vertex is isometric to a convex subset in the cone with vertex corresponding to the tip.

Note that the boundaries of all the Voronoi domains form a graph with straight edges. One can triangulate P so that each triangle has such edge as the base and the opposite vertex is the center of an adjusted Voronoi domain; such a vertex will be called *main* vertex of the triangle.

Fix a triangle $\triangle vab$ in the constructed triangulation; let v be its main vertex. Given a point $x \in \triangle$, set

$$\rho(x) = |x - v| \quad \text{and} \quad \theta(x) = \min\{\angle[v_x^a], \angle[v_x^b]\}.$$

Map x to the plane the point with polar coordinates $(\rho(x), \theta(x))$.

It is easy to see that the constructed map $\triangle \rightarrow \mathbb{R}^2$ is piecewise distance preserving. It remains to check that the constructed maps on all triangles agree on common sides. \square

This construction was given by Victor Zalgaller in [165], see also [123]. Svetlana Krat generalized the statement to the higher dimensions [see 166].

Piecewise linear extension. Let a_1, a_2, \dots, a_n and b_1, b_2, \dots, b_n be two collections of points in \mathbb{R}^2 such that $|a_i - a_j| \geq |b_i - b_j|$ for all pairs i, j . We need to construct a piecewise linear length-preserving map $f: \mathbb{R}^2 \rightarrow \mathbb{R}^2$ such that $f(a_i) = b_i$ for each i .

Assume that the problem is already solved if $n < m$; let us do the case $n = m$. By assumption, there is a piecewise linear length-preserving map $f: \mathbb{R}^2 \rightarrow \mathbb{R}^2$ such that $f(a_i) = b_i$ for each $i > 1$. Consider the set

$$\Omega = \{x \in \mathbb{R}^2 \mid |f(x) - b_1| > |x - a_1|\}.$$

If $\Omega = \emptyset$, then $f(a_1) = b_1$; that is, the problem is solved.

Prove that Ω is the interior of a polygon which is star-shaped with respect to a_1 . Redefine the map f inside Ω so that it remains piecewise linear length-preserving and $f(a_1) = b_1$. \square

The same proof works in all dimensions; it was given by Ulrich Brehm in [167]. The same proof was rediscovered by Arseniy Akopyan and Alexey Tarasov in [168], see also [123].

The problem is closely related to Kirszbraun's theorem [21], which was reproved by Frederick Valentine in [22]; the proof of Brehm uses the same idea.

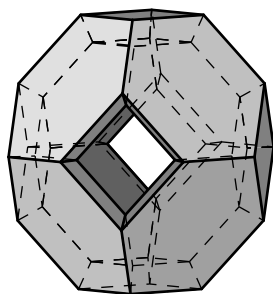
Closed polyhedral surface. Start with your favorite convex polyhedron K . Assume that the interior of K contains the origin $0 \in \mathbb{R}^3$.

Remove from K the interior of $K' = \lambda \cdot K$ for positive $\lambda < 1$.

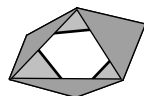
Note that one can drill from each vertex of K a polyhedral tunnel to the corresponding vertex K' so that the surface of obtained nonconvex polytope is a solution. \square

The construction above produces a surface of genus at least 3. One can also construct a polyhedral surface in \mathbb{R}^3 which is isometric to a flat torus. It follows from a very general result of Burgo and Zalgaller [see 169]. They show in particular that any short smooth embedding of a flat torus in \mathbb{R}^3 can be approximated by piecewise linear isometric embedding.

The following construction is more direct; it is a bent version of so called *Schwarz boot* [see 170]. Construct an isometric piecewise linear embedding of a cylinder as shown on the diagram such that the planes through the boundary triangles meet at the angle $\frac{\pi}{n}$ for a positive integer n . It remains to reflect the obtained surface several times in the planes through the boundary triangles.



The problem suggested by Jarosław Kędra.



Minimal polyhedron. Arguing by contradiction, assume a polyhedral surface T minimizes the area but not saddle.

Prove that one can move one of the vertices of T in such a way that the lengths of all edges starting at this vertex decrease.

Prove that if, by this deformation, the area does not decrease, then there are two adjacent triangles in the triangulation, say $\triangle pxy$ and $\triangle qxy$ such that

$$\angle[p_y^x] + \angle[q_y^x] > \pi.$$

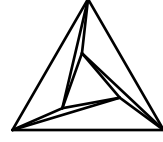
Finally show that in this case exchanging triangles $\triangle pxy$ and $\triangle qxy$ to the triangles $\triangle pxq$ and $\triangle pyq$ leads to a polyhedral surface with smaller area. That is, T is not area minimizing, a contradiction. \square

This problem is discussed in my paper [171].

For general polyhedral surface, the deformation which decreases the lengths of all edges may not decrease the area. Moreover, the surface

which minimize the area among all surfaces with fixed triangulation might be not saddle; try to construct such example.

Coherent triangulation. Look at the diagram and think. \square



The problem was discussed by Israel Gelfand, Mikhail Kapranov and Andrei Zelevinsky in [172, p. 7C].

Characterization of polytope. Arguing by contradiction, let us assume that $P \subset \mathbb{R}^m$ is a counterexample and m takes minimal possible value.

Choose a finite cover B_1, B_2, \dots, B_n of K , where $B_i = B(z_i, \varepsilon_i)$ and $B_i \cap P = B_i \cap K_i$, where K_i is a cone with the tip at z_i .

For each i , consider function $f_i(x) = |z_i - x|^2 - \varepsilon_i^2$. Note that

$$W_{i,j} = \{ x \in \mathbb{R}^m \mid f_i(x) = f_j(x) \}$$

is a hyperplane for any pair $i \neq j$.

The subset $P_{i,j} = P \cap W_{i,j}$ satisfies the same assumptions as P , but lies in a hyperplane. Since m is minimal, we get that $P_{i,j}$ is a polytope for any pair i, j .

Consider Voronoi domains

$$V_i = \{ x \in \mathbb{R}^m \mid f_i(x) \geq f_j(x) \text{ for any } j \}.$$

Note that $P \cap V_i$ is formed by the points which lie on the segments from z_i to a point in $P \cap \partial V_i$.

The statement follows since ∂V_i is covered by the hyperplanes $W_{i,j}$. \square

The problem is mentioned by Nina Lebedeva and me in [173].

A sphere with one edge. An example, say P , can be found among the spherical polyhedral spaces which admit an isometric \mathbb{S}^1 -action with geodesic orbits.

Fix large relatively prime integers $p > q$. Consider the triangle Δ with angles $\frac{\pi}{p}$, $\frac{\pi}{q}$ and say $\pi \cdot (1 - \frac{1}{p})$ in the sphere of radius $\frac{1}{2}$. Denote by $\hat{\Delta}$ the doubling of Δ in its boundary. Note that $\hat{\Delta}$ is homeomorphic to \mathbb{S}^2 , it has 3 singular points with total angles $2 \cdot \frac{\pi}{p}$, $2 \cdot \frac{\pi}{q}$ and $2 \cdot \pi \cdot (1 - \frac{1}{p})$.

Consider \mathbb{S}^1 -action on $\mathbb{S}^3 \subset \mathbb{C}^2$ by the diagonal matrices $\begin{pmatrix} z^p & 0 \\ 0 & z^q \end{pmatrix}$, $z \in \mathbb{S}^1 \subset \mathbb{C}$. Construct a spherical polyhedral metric ρ on \mathbb{S}^3 such that the \mathbb{S}^1 -orbits become geodesics and the quotient $(\mathbb{S}^3, \rho)/\mathbb{S}^1$ is isometric to $\hat{\Delta}$.

In the constructed example the singular points with total angles $2 \cdot \frac{\pi}{p}$ and $2 \cdot \frac{\pi}{q}$ should correspond to the points with isotropy groups \mathbb{Z}/p

and \mathbb{Z}/q of the action. The points in $P = (\mathbb{S}^3, d)$ on the orbits over these points will be regular points of P . The singular locus P^* of P will be formed by the orbit corresponding to the remaining singular point of $\hat{\Delta}$. By construction,

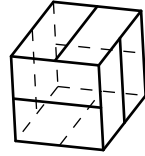
◇ P^* is a closed geodesic with angle $2 \cdot \pi \cdot (1 - \frac{1}{p})$ around it.

◇ P^* forms a (p, q) -torus knot in the ambient \mathbb{S}^3 . □

It is expected that only the torus knots can appear this way.

The construction given by Dmitri Panov in [174]. The cone K over P is a polyhedral space with natural complex structure; that is, one can cut simplices from \mathbb{C}^2 and glue the cone from them in such a way that complex structures will agree along the gluings. Moreover the cone K can be holomorphically parametrized by \mathbb{C}^2 in such a way that its singular set becomes an algebraic curve $z^p = w^q$ in some (z, w) -coordinates of \mathbb{C}^2 .

There is also a Euclidean polyhedral metrics on \mathbb{S}^3 with singularity formed by Borromean rings. It can be obtained by gluing each face of cube to it self along the reflections in the middle lines shown on the picture. This construction is due to William Thurston [see 175]



Triangulation of a torus. Let us equip the torus with the flat metric such that each triangle is equilateral. The metric will have two singular cone points, the first corresponds to the vertex v_5 with 5 triangles, the total angle around this point is $\frac{5}{3} \cdot \pi$ and the second corresponds to the vertex v_7 with 7 triangles, the total angle around this point is $\frac{7}{3} \cdot \pi$.

Prove the following.

Observation. The holonomy group of this metric is generated by rotation by $\frac{\pi}{3}$.

Consider a closed geodesic γ_1 which minimize the length of all circles which are not null-homotopic. Let γ_2 be an other closed geodesic which minimize the length and is not homotopic to any power of γ_1 .

Show that γ_1 and γ_2 intersect at a single point.

Show that γ_i cannot pass v_5 .

Apply the observation above to show that if γ_i pass through v_7 , then the measure of one of two angles which γ_i cuts at v_7 equals to π . Use the latter statement to show that one can push γ_i aside so it does not longer pass through v_7 , but remains a closed geodesic.

Cut \mathbb{T}^2 along γ_1 and γ_2 . In the obtained quadrilateral, connect v_5 to v_7 by a minimizing geodesic and cut along it. This way we obtain an annulus with flat metric. Look at the neighborhood of the boundary components and show that the annulus can and cannot be isometrically immersed into the plane; this is a contradiction. □

There are flat metrics on the torus with only two singular points which have the total angles $\frac{5}{3} \cdot \pi$ and $\frac{7}{3} \cdot \pi$. Such example can be obtained by identifying the hexagon on the picture according to the arrows. But the holonomy group of the obtained torus is generated by the rotation by angle $\frac{\pi}{6}$. In particular, the observation is necessary in the proof.

The same argument shows that holonomy group of flat torus with exactly two singular points with total angle $2 \cdot (1 \pm \frac{1}{n}) \cdot \pi$ has more than n elements. In the solution we did the case $n = 6$.

The problem was originally discovered and solved by Stanislav Jendrol' and Ernest Jucovič, in [176], their proof is combinatorial. The solution described above was given by Rostislav Matveyev in his lectures [see 177]. A complex-analytic proof was found by Ivan Izvestiev, Robert Kusner, Günter Rote, Boris Springborn and John Sullivan in [178].



No simple geodesics. The curvature of a vertex on the surface of a convex polyhedron is defined as the $2 \cdot \pi - \theta$, where θ is the total angle around the vertex.

Notice that a simple closed geodesic cuts the surface into two discs with total curvature $2 \cdot \pi$ each. Therefore it is sufficient to construct a convex polyhedron with curvatures of the vertices $\omega_1, \omega_2, \dots, \omega_n$ such that $2 \cdot \pi$ cannot be obtained as sum of some of ω_i . An example of that type can be found among 3-simplexes. \square

The problem is due to Gregory Galperin [see 179] and rediscovered by Dmitry Fuchs and Serge Tabachnikov [see 20.8 in 14].

Chapter 9

Discrete geometry

In this chapter we consider geometrical problems with strong combinatoric flavor. No special prerequisite is needed.

Round circles in \mathbb{S}^3

▮ *Suppose that you have a finite collection of pairwise linked round circles in the unit 3-sphere, not necessarily all of the same radius. Prove that there is an isotopy in the space of such collections of circles which moves all of them into great circles.*

Semisolution. For each circle consider the containing it plane in \mathbb{R}^4 . Note that the circles are linked if and only if the corresponding planes intersect at a single point inside \mathbb{S}^3 .

Take the intersection of the planes with the sphere of radius $R \geq 1$, rescale and pass to the limit as $R \rightarrow \infty$. This way we get needed isotopy. \square

The problem was discussed in the thesis of Genevieve Walsh [see 180].

Box in a box

▮ *Assume that a parallelepiped with sizes a, b, c lies inside another parallelepiped with sizes a', b', c' . Show that*

$$a' + b' + c' \geq a + b + c.$$

Harnack's circles

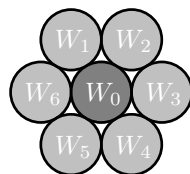
▮ Prove that a smooth algebraic curve of degree d in \mathbb{RP}^2 consists of at most $n = \frac{1}{2} \cdot (d^2 - 3 \cdot d + 4)$ connected components.

Two points on each line

▮ Construct a set in the Euclidean plane, which intersects each line at exactly 2 points.

Kissing number^o

Let W_0 be a convex body in \mathbb{R}^m . We say that k is the *kissing number* of W_0 (briefly $k = \text{kiss } W_0$) if k is the maximal integer such that there are k bodies W_1, W_2, \dots, W_k such that each W_i is congruent to W_0 , $W_i \cap W_0 \neq \emptyset$ for each i and have no pair W_i, W_j has common interior points.



Say, as you may guess from the diagram, the kissing number of round disc in the plane is 6.

▮ Show that for any convex body W_0 in \mathbb{R}^m

$$\text{kiss } W_0 \geq \text{kiss } B,$$

where B denotes the unit ball in \mathbb{R}^m .

Monotonic homotopy

▮ Let F be a finite set and $h_0, h_1: F \rightarrow \mathbb{R}^m$ be two maps. Consider \mathbb{R}^m as a subspace of $\mathbb{R}^{2 \cdot m}$. Show that there is a homotopy $h_t: F \rightarrow \mathbb{R}^{2 \cdot m}$ from h_0 to h_1 such that for any $x, y \in F$ the function

$$t \mapsto |h_t(x) - h_t(y)|$$

is monotonic.

Cube

▮ Half of the vertices of an m -dimensional cube are colored in white and the other half in black. Show that the cube has at least 2^{m-1} edges which connect the vertices of different colors.

Geodesic loop

☞ Show that the surface of cube in \mathbb{R}^3 does not admit a geodesic loop with the base point at a vertex.

Right and acute triangles

☞ Let $x_1, \dots, x_n \in \mathbb{R}^m$ be a collection of points such that any triangle $\triangle x_i x_j x_k$ is right or acute. Show that $n \leq 2^m$.

Right-angled polyhedron⁺

☞ Show that in all sufficiently large dimensions, there is no compact convex hyperbolic polyhedron with right dihedral angles.

Let us give a short summary of Dehn–Sommerville equations which can help you to solve this problem.

Assume P is a *simple* Euclidean m -dimensional polyhedron; that is, every vertex of P exactly m facets are meeting. Denote by f_k the number of k -dimensional faces of P ; the array of integers (f_0, f_1, \dots, f_m) is called f -vector of P .

Fix an order of the vertices v_1, v_2, \dots, v_{f_0} of P so that for some linear function ℓ , we have $\ell(v_i) > \ell(v_j) \Leftrightarrow i < j$. The *index* of the vertex v_i is defined as the number of edges $[v_i v_j]$ such that $j < i$. The number of vertices of given index k will be denoted as h_k . The array of integers (h_0, h_1, \dots, h_m) is called h -vector of P . Clearly $h_0 = h_m = 1$ and $h_k \geq 0$ for all k .

Each k -face of P contains unique vertex which maximize ℓ ; if the vertex has index i , then $i \geq k$ and then it is the maximal vertex for exactly $\frac{i!}{k! \cdot (i-k)!}$ faces of dimension k . This observation can be packed in the following polynomial identity

$$\sum_k h_k \cdot (t+1)^k = \sum_k f_k \cdot t^k.$$

Note that the identity above implies that h -vector does not depend on the choice of order of the vertices. In particular, the h vector is the same for the reversed order; that is

$$h_k = h_{m-k}$$

for any k . These identities are called Dehn–Sommerville equations. It gives the complete list of linear equations for h -vectors (and therefore f -vectors) of simple polyhedrons.

Balls without gaps

☞ Let B_1, \dots, B_n be the balls of radii r_1, \dots, r_n in a Euclidean space. Assume that no hyperplane divides the balls into two non-empty sets without intersecting at least one of the balls. Show that the balls B_1, \dots, B_n can be covered by a ball of radius $r = r_1 + \dots + r_n$.

Semisolutions

Box in a box. Let Π be a parallelepiped with dimensions a, b and c . Denote by $v(r)$ the volume of r -neighborhoods of Π ,

Note that for all positive r we have

$$(*) \quad v(r) = w_3 + w_2 \cdot r + w_1 \cdot r^2 + w_0 \cdot r^3,$$

where

- ◇ $w_0 = \frac{4}{3} \cdot \pi$ is the volume of unit ball,
- ◇ $w_1 = \pi \cdot (a + b + c)$,
- ◇ $w_2 = 2 \cdot (a \cdot b + b \cdot c + c \cdot a)$ is the surface area of Π ,
- ◇ $w_3 = a \cdot b \cdot c$ is the volume of Π ,

Assume Π' be an other parallelepiped with dimensions a', b' and c' . For the volume $v'(r)$ the volume of r -neighborhoods of Π' we have a formula similar (*).

Note that if $\Pi \subset \Pi'$, then $v(r) \leq v'(r)$ for any r . Checking this inequality for $r \rightarrow \infty$, we get

$$a + b + c \leq a' + b' + c'.$$

□

The problem was discussed by Alexander Shen in [181].

A formula analogous to (*) holds for arbitrary convex body B in arbitrary dimension m . The coefficient $w_i(B)$ in the polynomial with different normalization constants appear under different names most commonly *intrinsic volume* and *quermassintegral*. They also can be defined as the average of area of projections of B to the i -dimensional planes. In particular if B' and B are convex bodies such that $B' \subset B$, then $w_i(B') \leq w_i(B)$ for any i . This generalize our problem quite a bit. Further generalizations lead to so called *mixed volumes* [see 182].

Harnack's circles. Let $\sigma \subset \mathbb{RP}^2$ be a smooth algebraic curve of degree d . Consider the complexification $\Sigma \subset \mathbb{CP}^2$ of σ . Without loss of generality, we may assume that Σ is regular.

Prove that all regular complex algebraic curves of degree d in \mathbb{RP}^2 are homeomorphic to each other; denote by g their genus. Perturbing a singular curve formed by d lines in \mathbb{CP}^2 , we get that

$$g = \frac{1}{2} \cdot (d-1) \cdot (d-2).$$

The real curve σ forms the fixed point set in Σ by the complex conjugation. Use it to show that $\Sigma \setminus \sigma$ has at most 2 connected components. Hence the result follows. \square

The inequality was originally proved by Axel Harnack with a different method [see 183]. The idea to use complexification is due to Felix Klein [see 184]. This problem formed the background to Hilbert's 16th problem [see 130].

Two points on each line. Take any complete ordering of the set of all lines so that each beginning interval has cardinality less than continuum.

Assume we have a set of points X such that each line intersects X at at most 2 points and cardinality of X is less than continuum.

Choose the least line ℓ in the ordering which intersect X by 0 or 1 point. Note that the set of all lines intersecting X at two points has cardinality less than continuum. Therefore we can choose a point on ℓ and add it to X so that the remaining lines are not overloaded.

It remains to apply well ordering principle. \square

The following problem look similar but far more involved; a solution follows from the proof that a square cannot be cut into triangles of equal area given by Paul Monsky in [185].

\diamond *Subdivide the plane into three everywhere dense sets A , B and C such that each line meets exactly two of these sets.*

Kissing number. Let $n = \text{kiss } B^m$ and B_1, B_2, \dots, B_n the the copies of B which touch B and have no common interior points. For each B_i consider the vector v_i from the center of B to the center of B_i . Note that $\angle(v_i, v_j) \geq \frac{\pi}{3}$ if $i \neq j$.

For each i , consider supporting hyperplane Π_i to W with outer normal vector v_i . Denote by W_i the reflection of W in Π_i .

Prove that W_i and W_j have no common interior points if $i \neq j$; the latter gives the needed inequality. \square

The proof is given by Charles Halberg, Eugene Levin and Ernst Straus in [186]. It is expected that the same inequality holds for the orientation-preserving version of kissing number.

Monotonic homotopy. Note that we can assume that $h_0(F)$ and $h_1(F)$ both lie in the coordinate m -spaces of $\mathbb{R}^{2 \cdot m} = \mathbb{R}^m \times \mathbb{R}^m$; that is, $h_0(F) \subset \mathbb{R}^m \times \{0\}$ and $h_1(F) \subset \{0\} \times \mathbb{R}^m$.

Show that the following homotopy is monotonic

$$h_t(x) = (h_0(x) \cdot \cos \frac{\pi \cdot t}{2}, h_1(x) \cdot \sin \frac{\pi \cdot t}{2}). \quad \square$$

This homotopy was discovered by Ralph Alexander in [187]. It has number of applications, one of the most beautiful is the given by Károly Bezdek and Robert Connelly [188] in their proof of Kneser–Poulsen and Klee–Wagon conjectures in dimension 2.

The dimension $2 \cdot m$ is optimal; that is, for any positive integer m , there are two maps $h_0, h_1: F \rightarrow \mathbb{R}^m$ which cannot be connected by a monotonic homotopy $h_t: F \rightarrow \mathbb{R}^{2 \cdot m-1}$. The latter was shown by Maria Belk and Robert Connelly in [189]

Cube. Consider the cube $[-1, 1]^m \subset \mathbb{R}^m$. Any vertex this cube has the form $\mathbf{q} = (q_1, q_2, \dots, q_m)$, where $q_i = \pm 1$.

For each vertex \mathbf{q} , consider the intersection of the corresponding octant with the unit sphere; that is, the set

$$V_{\mathbf{q}} = \{ (x_1, x_2, \dots, x_m) \in \mathbb{S}^{m-1} \mid q_i \cdot x_i \geq 0 \text{ for each } i \}.$$

Consider the set $\mathcal{A} \subset \mathbb{S}^{m-1}$ formed by the union of all the sets $V_{\mathbf{q}}$ for $\mathbf{q} \in A$. Note that

$$\text{vol}_{m-1} \mathcal{A} = \frac{1}{2} \cdot \text{vol}_{m-1} \mathbb{S}^{m-1}$$

and

$$\text{vol}_{m-2} \partial \mathcal{A} = \frac{k}{2^{m-1}} \cdot \text{vol}_{m-2} \mathbb{S}^{m-2},$$

where k is the number of edges of the cube with one end in A and the other in B .

It remains to show that

$$\text{vol}_{m-2} \partial \mathcal{A} \geq \text{vol}_{m-2} \mathbb{S}^{m-2}.$$

The latter follows from the isoperimetric inequality for \mathbb{S}^m . \square

The problem was suggested by Greg Kuperberg [see 152].

Geodesic loop. Assume such loop exists; denote it by γ and let v be its base point.

Denote by ξ and ζ the directions of exit and the entrance of the loop. Let α be the angle between ξ and ζ measured in the tangent cone to the surface of cube at v .

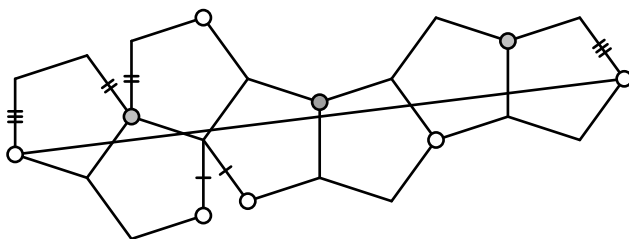
Prove that $\alpha = \frac{\pi}{2}$. To do this you can use Gauss–Bonnet theorem or unfolding.

It follows that there is a rotational symmetry of cube which fix v and sends ξ to ζ . The later leads to a contradiction. \square

For the surface of a higher dimensional cube, the same idea provides existence of symmetry of the cube which fix v and swaps ξ and ζ . From this point one can arrive to a contradiction, but the work is harder than above.

The same statement holds for tetrahedron, octahedron and icosahedron. In this case α is a multiple of $\frac{\pi}{3}$; it implies existence of rotational symmetry of which fix v and sends ξ to ζ and leads to a contradiction the same way.

For the dodecahedron such loop exists; its development shown on the diagram. (The vertexes of a cube inscribed in the dodecahedron are circled.)



The problem suggested by Jarosław Kędra.

Right and acute triangles. Denote by K the convex hull of $\{x_1, \dots, x_n\}$. Without loss of generality we can assume that K is nondegenerate polytope. Prove the following claim. \square

For any distinct x_i and x_j and any interior point z in K we have

$$\angle[x_i \atop z]^{x_j} < \frac{\pi}{2}.$$

Denote by h_i the homothety with center at x_i and coefficient $\frac{1}{2}$. Set $K_i = h_i(K)$.

Let us show that K_i and K_j have no common interior point. Assume contrary; that is $z = h_i(z_i) = h_j(z_j)$; for some interior points z_i and z_j in K . Note that

$$\angle[x_i \atop z_i]^{x_j} + \angle[x_j \atop z_j]^{x_i} = \pi,$$

which contradicts the claim.

Note that $K_i \subset K$ for any i ; it follows that

$$\begin{aligned} \frac{m}{2^n} \cdot \text{vol } K &= \sum_{i=1}^m \text{vol } K_i \leq \\ &\leq \text{vol } K. \end{aligned}$$

Hence the result follows. \square

The problem was posted by Paul Erdős in [190] and solved by Ludwig Danzer and Branko Grünbaum in [191]. Under the name *Angels in Space*, this problem appears in the *connoisseur's collection* [192] of Peter Winkler.

Grigori Preleman noticed that the same proof works for a similar problem for Alexandrov space [see 193]; the later led to interesting connections to the crystallographic groups [see 194].

The upper bound for the number of points with only acute triangles grows exponentially with m ; the later was shown by Paul Erdős and Zoltán Füredi in [195]; the proof use so called *probabilistic method*.

Right-angled polyhedron. Let P be a right-angled hyperbolic polyhedron of dimension m . Note that P is simple; that is, exactly m facets meet at each vertex of P .

From the projective model of hyperbolic plane, one can see that for any simple compact hyperbolic polyhedron there is a simple Euclidean polyhedron with the same combinatorics. In particular Dehn–Sommerville equations hold for P .

Denote by (f_0, f_1, \dots, f_m) and (h_0, h_1, \dots, h_m) the f - and h -vectors of P . Recall that $h_i \geq 0$ for any i and $h_0 = h_m = 1$. By Dehn–Sommerville equations, we get

$$(*) \quad f_2 > \frac{m-2}{4} \cdot f_1.$$

Since P is hyperbolic, each 2-dimensional face of P has at least 5 sides. It follows that

$$f_2 \leq \frac{m-1}{5} \cdot f_1.$$

The latter contradicts $(*)$ for $m \geq 6$. \square

The proof above is the core of proof of nonexistence of compact hyperbolic Coxeter's polyhedra of large dimensions given by Ernest Vinberg in [196], see also [197].

Playing a bit more with the same inequalities, one gets nonexistence of right-angled hyperbolic polyhedra, in all dimensions starting from 5. In 4-dimensional case, an example of a bonded right-angled hyperbolic polyhedron can be found among regular *120-cells* — the 4-dimensional brothers of dodecahedra.

Balls without gaps. Assume that each ball has the mass proportional to its radius. Denote by z the center of mass of the balls.

Show that all balls lie in the ball $B(z, r)$. \square

The statement was conjectured by Paul Erdős. The solution is given by Adolph and Ruth Goodmans in [198]. A variation was given later by Hugo Hardwiger in [hadwiger].

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