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# Metric Structures for Riemannian and Non-Riemannian Spaces

Misha Gromov

With Appendices by  
M. Katz, P. Pansu, and S. Semmes

English translation  
by Sean Michael Bates

Reprint of the 2001 Edition

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Based on *Structures Métriques des Variétés Riemanniennes*

Edited by J. LaFontaine and P. Pansu



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*...Meme ceux qui furent favorables à ma perception des vérités que je voulais ensuite graver dans le temple, me félicitèrent de les avoir découvertes au microscope, quand je m'étais au contraire servi d'un télescope pour apercevoir des choses, très petites en effet, mais parce qu'elles étaient situées à une grande distance, et qui étaient chacune un monde.*

**Marcel Proust**, *Le temps retrouvé*  
(Pléiade, Paris, 1954, p. 1041)

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# Preface to the French Edition

This book arose from a course given at the University of Paris VII during the third trimester of 1979. My purpose was to describe some of the connections between the curvature of a Riemannian manifold  $V$  and some of its global properties. Here, the word *global* refers not only to the topology of  $V$  but also to a family of metric invariants, defined for Riemannian manifolds and mappings between these spaces. The simplest metric invariants of such  $V$  are, for example, its volume and diameter; an important invariant of a mapping from  $V_1$  into  $V_2$  is its dilatation. In fact, such invariants also appear in a purely topological context and provide an important link between the given infinitesimal information about  $V$  (usually expressed as some restriction on the curvature) and the topology of  $V$ .

For example, the classical Gauss–Bonnett theorem gives an upper bound for the diameter of a positively curved manifold  $V$ , from which one can deduce the finitude of the fundamental group of  $V$ . For a deeper topological study of Riemannian manifolds, we need more subtle invariants than diameter or volume; I have attempted to present a systematic treatment of these invariants, but this treatment is far from exhaustive.

Messrs. J. Lafontaine and P. Pansu have successfully completed the almost insurmountable task of transforming into a rigorous mathematical text the chaos of my course, which was scattered with imprecise statements and incomplete proofs. I thank them as well as M. Berger, without whose assistance and encouragement this book would never have come into being. I also thank the *Editions Cedic* for the liberty it afforded the authors at the time that the book was edited.

M. Gromov  
Paris, June 1980

# Preface to the English Edition

The metric theory described in this book covers a domain stretching somewhere between the fields of topology and global Riemannian geometry. The boundary of this domain has dramatically exploded since 1979 and accordingly, in the course of its translation from the 1979 French version into English, the book has approximately quadrupled in size, even though I tried not to maim the original text with unnecessary incisions, insertions, and corrections, but rather to add several new sections indicated by the  $+$  subscript. The most voluminous additions are Chapter  $3\frac{1}{2}+$ , which attempts to link geometry and probability theory, and Appendix  $B_+$ , where an analyst lays down his view on metric spaces. Here, the reader can painlessly learn several key ideas of real analysis made accessible to us geometers by the masterful exposition of Stephen Semmes, who has adapted his material to our non-analytic minds.

Additionally, Appendix  $C_+$  reproduces my 1980-rendition of Paul Levy's inequality, while Misha Katz gives an overview of systolic freedom in Appendix  $D_+$ .

*Acknowledgements:* The initiative to publish an English translation of the book with Birkhäuser is due to Alan Weinstein. It was my pleasure to cooperate with Sean Bates, who translated the original version of the book and helped me edit the new sections. I am also grateful to Marcel Berger, Keith Burns, and Richard Montgomery for calling my attention to errors in the first version of the book.

**M. Gromov**  
*Bures-sur-Yvette, May 1997*

# Introduction: Metrics Everywhere

The conception of “distance” is already present in everyday language where it refers to two physical objects or two abstract ideas being mutually close or far apart. The most common (but by no means most general) mathematical incarnation of this vague idea is the notion of *metric space*, that is, an abstract set  $X$  where the distance between its elements, called *points*  $x \in X$ , is measured by *positive real numbers*. Thus a metric space is a set  $X$  with a given function in two variables, say  $d : X \times X \rightarrow \mathbb{R}_+$  satisfying the famous *triangle inequality*

$$d(x, x'') \leq d(x, x') + d(x', x'')$$

for all triples of points  $x, x'$  and  $x''$  in  $X$ .

Besides, one insists that the distance function be *symmetric*, that is,  $d(x, x') = d(x', x)$ . (This unpleasantly limits many applications: the effort of climbing up to the top of a mountain, in real life as well as in mathematics, is not at all the same as descending back to the starting point).

Finally, one assumes  $d(x, x) = 0$  for all  $x \in X$  and add the following *separation axiom*. If  $x \neq x'$ , then  $d(x, x') > 0$ . This seems to be an innocuous restriction, as one can always pass to the quotient space by identifying  $x$  and  $x'$  whenever  $d(x, x') = 0$ . But sometimes the separation becomes a central issue, e.g., for *Kobayashi* and *Hofer* metrics, where such identification may reduce  $X$  to a single point, for instance).

The archtypical example of a metric space is the ordinary Euclidean space  $\mathbb{R}^n$  with the pythagorean distance between the points  $x = (x_1, \dots, x_n)$  and  $x' = (x'_1, \dots, x'_n)$  defined by

$$d(x, x') = \sqrt{(x_1 - x'_1)^2 + \dots + (x_n - x'_n)^2}.$$

Next come subsets in  $\mathbb{R}^n$  with this metric providing many appealing examples, such as *the sphere*  $S^{n-1} = \{x \in \mathbb{R}^n \mid \sum_{i=1}^n x_i^2 = 1\}$  and the set

of vertices of the unit cube, i.e.,  $\{0, 1\}^n \subset \mathbb{R}^n$  with the *induced Euclidean* (pythagorean) distance. If  $X$  is a smooth connected submanifold in  $\mathbb{R}^n$  (as the above sphere) then, besides the induced Euclidean distance  $\text{dist}_{\mathbb{R}^n}$  on  $X$ , one has the *induced Riemannian distance*,  $\text{dist}_X(x, x')$  defined as the infimum of lengths of curves *contained in*  $X$  and joining  $x$  and  $x'$ . (One may be tempted to use the above as a quick definition of a Riemannian metric. Indeed, every Riemannian manifold admits a smooth embedding into some  $\mathbb{R}^n$  preserving the length of the curves according to the Nash theorem. But Euclidean embeddings hide rather than reveal the true metric structure of Riemannian manifolds due to uncontrolled distortion  $\text{dist}_X \neq \text{dist}_{\mathbb{R}^n}$ . Besides the full beauty and power of Riemannian geometry depend not only on the metric but also on the associated elliptic Riemannian equations, such as Laplace–Hodge, Dirac, Yang–Mills, and so on. These naturally come along with the Riemannian tensor but are nearly invisible on  $X$  embedded to  $\mathbb{R}^n$ .

Our approach to general metric spaces bears the undeniable imprint of early exposure to Euclidean geometry. We just love spaces sharing a common feature with  $\mathbb{R}^n$ . Thus there is a long tradition of the study of *homogeneous* spaces  $X$  where the isometry group acts *transitively* on  $X$ . (In the Riemannian case the metric on such  $X$  is fully determined by prescribing a positive definite quadratic form  $g_o$  on a single tangent space  $T_{x_o}(X)$ . But the simplicity of this description is illusory; it is quite hard to evaluate metric invariants of  $X$  in terms of  $g_o$ . For example, one has a very limited idea of how *systoles* (see below) behave as one varies a left invariant metric on a Lie group  $SO(n)$  or  $U(n)$  for instance.) Besides isometries,  $\mathbb{R}^n$  possesses many nontrivial *self-similarities*, i.e., transformations  $f$ , such that  $f^*(\text{dist}) = \lambda \text{ dist}$  for some constant  $\lambda \neq 0, 1$ . There are no self-similar spaces besides  $\mathbb{R}^n$  in the Riemannian category — this is obvious — but there are many such non-Riemannian examples such as  $p$ -adic vector spaces (these are totally disconnected) and some connected nilpotent Lie groups (e.g., the *Heisenberg group*) with Carnot–Carathéodory metrics (see 1.4, 1.18 and 2.6 in Appendix B).

Switching the mental wavelength, one introduces spaces with curvature  $K \leq 0$  and  $K \geq 0$  by requiring their small geodesic triangles to be “thinner” (correspondingly, “thicker”) than the Euclidean ones (see 1.19+). Here one is guided by the geometry of *symmetric spaces* that are distinguished homogeneous spaces, such as  $S^n$  and  $\mathbb{C}P^n$  where  $K \geq 0$  and  $SL_n \mathbb{R}/SO(n)$  with  $K \leq 0$ .

Apart from direct Euclidean descendants there are many instances of metrics associated to various structures, sometimes in a rather unexpected and subtle way. Here are a few examples.

*Complex manifolds.* The complex space  $\mathbb{C}^n, n \geq 1$ , carries no metric invariant under holomorphic automorphisms. There are just too many of them! Yet, many complex (and almost complex) manifolds, e.g., *bounded* domains in  $\mathbb{C}^n$ , do possess such natural metrics, for example, the *Kobayashi metric* (see 1.8 bis<sub>+</sub>).

*Symplectic manifolds.* No such manifold  $X$  of positive dimension carries an invariant metric, again because the group of symplectomorphisms is too large. Yet, the infinite dimensional space of closed *lagrangian* submanifolds in  $X$  (or rather each “hamiltonian component” of this space) does admit such a metric. (The construction of the metric is easy but the proof of the separation property, due to Hofer, is quite profound. Alas, we have no room for Hofer’s metric in our book).

*Homotopy category.* Once can functorially associate an infinite dimensional metric polyhedron to the homotopy class of each topological space  $X$ , such that continuous maps between spaces transform to distance decreasing maps between these polyhedra. Amazingly, the metric invariants of such polyhedra (e.g., its systoles, the volumes of minimal subvarieties realizing prescribed homology classes) lead to new homotopy invariants which are most useful for (aspherical) spaces  $X$  with large fundamental groups (see Ch. 5H<sub>+</sub>).

*Discrete groups.* A group with a distinguished finite set of generators carries a natural discrete metric which only moderately, i.e., bi-Lipschitzly, changes with a change of generators. Then, by adopting ideas from the geometry of noncompact Riemannian manifolds, one defines a variety of asymptotic invariants of infinite groups that shed new light on the whole body of group theory (see 3C, 5B, and 6B, C).

**Lipschitz and bi-Lipschitz.** What are essential maps between metric spaces? The answer “isometric” leads to a poor and rather boring category. The most generous response “continuous” takes us out of geometry to the realm of pure topology. We mediate between the two extremes by emphasizing *distance decreasing maps*  $f : X \rightarrow Y$  as well as general  $\lambda$ -*Lipschitz* maps  $f$  which enlarge distances at most by a factor  $\lambda$  for some  $\lambda \geq 0$ .

Isomorphisms in this category are  $\lambda$ -*bi-Lipschitz homeomorphisms* and most metric invariants defined in our book transform in a  $\lambda$ -controlled way under  $\lambda$ -Lipschitz maps, as does for example, the *diameter* of a space,  $\text{Diam } X = \sup_{x,x'} \text{dist}(x, x')$ . We study several classes of such invariants with a special treatment of *systoles* measuring the minimal volumes of homology classes in  $X$  (see Ch. 4 and App. D) and of *isoperimetric profiles* of complete Riemannian manifolds and infinite groups which are linked in

Ch. 6 to quasiconformal and quasiregular mappings.

**Asymptotic viewpoint.** Since every diffeomorphism between *compact* Riemannian manifolds is  $\lambda$ -bi-Lipschitz for some  $\lambda < \infty$ , our invariants tell us preciously little if we look at a *fixed compact* manifold  $X$ . What is truly interesting in the  $\lambda$ -Lipschitz environment is the metric behavior of *sequences* of compact spaces. This ideology applies, for example, to an individual *noncompact* space  $X$ , where the asymptotic geometry may be seen as  $X$  is exhausted by a growing sequence of compact subspaces. We also study sequences of maps and homotopy classes of maps between fixed compact spaces, say  $f_i : X \rightarrow Y$  (see Ch. 2, 7) and relate this asymptotic metric behavior to the homotopy structure of  $X$  and  $Y$  (with many fundamental questions remaining open).

**Metric sociology.** As our perspective shifts from individual spaces  $X$  to families (e.g., sequences) of these, we start looking at all metric spaces simultaneously and observe that there are several satisfactory notions of distance *between* metric spaces (see Ch. 3). Thus we may speak of various kinds of metric convergence of a sequence  $X_i$  to a space  $X$  and study the asymptotics of particular sequences. For example, if  $X_i$ ,  $i = 1, 2, \dots$ , are Riemannian manifolds of dimension  $n$  with a fixed bound on their sectional curvatures, then there is a subsequence that converges (or collapses) to a mildly singular space of dimension  $m < n$  (see Ch. 8).

**Metric, Measure and Probability.** Suppose our metric spaces are additionally given some measures, e.g., the standard Riemannian measures if we deal with compact Riemannian manifolds. Here one has several notions of metric convergence of spaces modulo subsets of measure  $\rightarrow 0$  (see Ch.  $3\frac{1}{2}_+$ ). Then there is a weaker convergence most suitable for sequences  $X_i$  with  $\dim X_i \rightarrow \infty$ . According to this, unit spheres  $S^i \subset \mathbb{R}^{i+1}$  with normalized Riemannian measures converge (or concentrate, see  $3\frac{1}{2}_+$ ) to a single atom of unit mass! This can be regarded as a geometric version of the *law of large numbers* that is derived in the present case from the *spherical isoperimetric inequality* (see  $3\frac{1}{2}_+$ E and Appendix C).

**From local to global.** This is a guiding principle in geometry as well as in much of analysis, and the reader will find it in all corners of our book. It appears most clearly in Ch. 5 where we explain how the lower bound on the *Ricci curvature of a manifold  $X$*  implies the *measure doubling property*, saying that the volume of each not very large  $2r$ -ball  $B(2r) \subset X$  does not exceed  $\text{const Vol } B(r)$  for the concentric ball  $B(r) \subset B(2r)$ . This leads to several topological consequences concerning the fundamental group of  $X$  (see Ch. 5).

Besides the volumes of balls, the Ricci curvature controls the isoperimetric profile of  $X$ . For example, the spherical isoperimetric inequality generalizes to the manifolds with  $\text{Ricci} \geq -\text{const}$  (see Appendix C).

**Analysis on metric spaces.** Smooth manifolds and maps, being infinitesimally linear, appear plain and uneventful when looked upon through a microscope. But singular fractal spaces and maps display a kaleidoscopic variety of patterns on all local scales. Some of these spaces and maps are sufficiently regular, e.g., they may possess the doubling property, and provide a fertile soil for developing rich geometric analysis. This is exposed by Stephen Semmes in Appendix B.

I have completed describing what is in the book. It would take another volume just to indicate the full range of applications of the metric idea in various domains of mathematics.

**Misha Gromov**

April 1999

# Chapter 1

# Length Structures: Path Metric Spaces

## Introduction

In classical Riemannian geometry, one begins with a  $C^\infty$  manifold  $X$  and then studies smooth, positive-definite sections  $g$  of the bundle  $S^2T^*X$ . In order to introduce the fundamental notions of covariant derivative and curvature (cf. [Grl–Kl–Mey] or [Milnor]MT, Ch. 2), use is made only of the differentiability of  $g$  and not of its positivity, as illustrated by Lorentzian geometry in general relativity. By contrast, the concepts of the length of curves in  $X$  and of the geodesic distance associated with the metric  $g$  rely only on the fact that  $g$  gives rise to a family of continuous norms on the tangent spaces  $T_x X$  of  $X$ . We will study the associated notions of length and distance for their own sake.

## A. Length structures

**1.1. Definition:** The *dilatation* of a mapping  $f$  between metric spaces  $X, Y$  is the (possibly infinite) number

$$\text{dil}(f) = \sup_{\substack{x, x' \in X \\ x \neq x'}} \frac{d(f(x), f(x'))}{d(x, x')},$$

where “ $d$ ” stands for the metrics (distances)  $\text{dist}_X$  in  $X$  and  $\text{dist}_Y$  in  $Y$ . The local dilatation of  $f$  at  $x$  is the number

$$\text{dil}_x(f) = \lim_{\varepsilon \rightarrow 0} \text{dil}(f|_{B(x, \varepsilon)}).$$

A map  $f$  is called *Lipschitz* if  $\text{dil}(f) < \infty$ ; it is called  $\lambda$ -*Lipschitz* if  $\text{dil}(f) \leq \lambda$ , in which case, the infimal such  $\lambda$  is called the *Lipschitz constant* of  $f$ .

If  $f$  is a Lipschitz mapping of an interval  $[a, b]$  into  $X$ , then the function  $t \mapsto \text{dil}_t(f)$  is measurable.

**1.2. Definition:** The *length* of a Lipschitz map  $f : [a, b] \rightarrow X$  is the number

$$\ell(f) = \int_a^b \text{dil}_t(f) dt.$$

If  $f$  is merely continuous, we can define  $\ell(f)$  as the supremum of all sums of the form  $\sum_{i=0}^n d(f(t_i), f(t_{i+1}))$  where  $a = t_0 \leq t_1 \leq \dots \leq t_{n+1} = b$  is a finite partition of  $[a, b]$ .

If  $\varphi$  is a homeomorphism of a closed interval  $I'$  onto  $I = [a, b]$ , then  $\ell$  satisfies  $\ell(f \circ \varphi) = \ell(f)$ , as follows from the fact that  $\varphi$  is strictly monotone (invariance under change of parameter).

The two definitions of  $\ell(f)$  stated above are equivalent when  $f$  is absolutely continuous (cf. [Rinow], p. 106). This fact permits us to define  $\ell(f)$  as the integral of the local dilatation when  $f$  is Lipschitz and to set  $\ell(f \circ \varphi) = \ell(f)$  for each homeomorphism  $\varphi$  of  $I$  onto  $I'$ . More generally,

**1.3. Definition:** A *length structure* on a set  $X$  consists of a family  $\mathcal{C}(I)$  of mappings  $f : I \rightarrow X$  for each interval  $I$  and a map  $\ell$  of  $\mathcal{C} = \bigcup \mathcal{C}(I)$  into  $\mathbb{R}$  having the following properties:

- (a) **Positivity:** We have  $\ell(f) \geq 0$  for each  $f \in \mathcal{C}$ , and  $\ell(f) = 0$  if and only if  $f$  is constant (we assume of course that the constant functions belong to  $\mathcal{C}$ ).
- (b) **Restriction, juxtaposition:** If  $I \subset J$ , then the restriction to  $I$  of any member of  $\mathcal{C}(J)$  is contained in  $\mathcal{C}(I)$ . If  $f \in \mathcal{C}([a, b])$  and  $g \in \mathcal{C}([b, c])$ , then the function  $h$  obtained by juxtaposition of  $f$  and  $g$  lies in  $\mathcal{C}([a, c])$  and  $\ell(h) = \ell(f) + \ell(g)$ .
- (c) **Invariance under change of parameter:** If  $\varphi$  is a homeomorphism from  $I$  onto  $J$  and if  $f \in \mathcal{C}(J)$ , then  $f \circ \varphi \in \mathcal{C}(I)$  and  $\ell(f \circ \varphi) = \ell(f)$ .
- (d) **Continuity:** For each  $I = [a, b]$ , the map  $t \mapsto \ell(f|_{[a, t]})$  is continuous.

Using conditions (a), (b), and (c), we can define a pseudo-metric  $d_\ell$  on  $X$  called the *length metric* by setting

$$d_\ell(x, y) = \inf\{\ell(f) : f \in \mathcal{C}, x, y \in \text{im}(f)\}.$$

As usual, this pseudo-metric induces a topology on  $X$ .

It is common to define  $\ell(f) = \infty$  when the map  $f : I \rightarrow X$  is not contained in  $\mathcal{C}(I)$ .

#### 1.4. Examples:

(a) A metric space  $(X, d)$  is equipped with a canonical length structure: The set  $\mathcal{C}$  consists of all continuous mappings from intervals into  $X$ , and the function  $\ell$  is defined as in 1.2 above. The resulting structure is called the *metric length structure* of  $(X, d)$ ; in general, however, the length metric  $d_\ell$  differs from  $d$ , and their corresponding topologies may also be distinct.

(b<sub>+</sub>) *Tits-like metrics and snowflakes*: Consider  $\mathbb{R}^n$  equipped with polar coordinates  $(r, s)$ , where  $r \in [0, \infty)$  and  $s \in S^{n-1}$ , the unit sphere in  $\mathbb{R}^n$ . Define

$$d(x_1, x_2) = |r_1 - r_2| + r\|s_1 - s_2\|^{1/2},$$

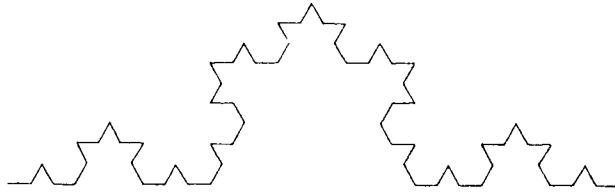
where  $x_i = (r_i, s_i) \in \mathbb{R}^n$ ,  $i = 1, 2$ ,  $\|s_1 - s_2\|$  denotes the Euclidean distance on  $S^{n-1} \subset \mathbb{R}^n$ , and  $r = \min\{r_1, r_2\}$ . This  $d$  gives rise to the usual topology on  $\mathbb{R}^n$ , but

$$d_\ell(x_1, x_2) = \begin{cases} |r_1 - r_2| & \text{for } s_1 = s_2 \\ r_1 + r_2 & \text{for } s_1 \neq s_2, \end{cases}$$

and so  $(\mathbb{R}^n, d_\ell)$  becomes the *disjoint* union of the Euclidean rays  $[0, \infty) \times s$  for all  $s \in S^{n-1}$ , all glued together at the origin only. In particular, the unit sphere  $S^{n-1} \subset \mathbb{R}^n$  is discrete with respect to  $d_\ell$ . Metrics of this type naturally appear on (the ideal boundaries of) manifolds with nonpositive sectional curvatures and are collectively referred to as *Tits metrics* (cf. [Ba–Gr–Sch]).

An analog of the metric  $d_\ell$  can be constructed on the subset of Euclidean 3-space consisting of the straight cone  $X \subset \mathbb{R}^3$  over the Koch snowflake  $S \subset \mathbb{R}^2$ . (Here, the snowflake is the base of the cone and plays the role of the sphere  $S^{n-1}$  in the Tits-like example above). The only curves in  $X$  having finite Euclidean length are those contained in the (straight) generating lines of the cone, and so these lines are disjoint with respect to  $d_\ell$  away from the vertex (compare [Rinow], p. 117, and Appendix B<sub>+</sub> of this book).

In general, the metrics  $d, d_\ell$  always satisfy the inequality  $d \leq d_\ell$ , so that their corresponding topologies coincide if and only if for each  $x \in X$  and  $\varepsilon > 0$ , there exists a  $d$ -neighborhood of  $x$  in which each point is connected to  $x$  by a curve of length at most  $\varepsilon$ .

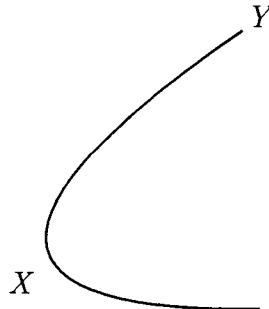


(c) If  $X$  is a manifold, then any Riemannian or Finslerian structure on  $X$  naturally gives rise to a length structure: One proceeds as in 1.2, noting that when  $f$  is differentiable, its local dilatation at a point  $x$  equals the norm of its derivative at  $x$ .

(d) *Induced length structures:* If  $X$  is equipped with a length structure and  $\varphi$  is a map from a set  $Y$  into  $X$ , then we obtain a length structure on  $Y$  by setting

$$\ell_Y(f) = \ell_X(\varphi \circ f)$$

for each  $f: I \rightarrow Y$ .



(e) *First exposure to Carnot–Caratheodory spaces.* We can associate a length structure on a Riemannian manifold  $(V, g)$  with any tangent subbundle  $E \subset TV$  by defining the length of a curve  $c$  to be its usual Riemannian length if  $c$  is absolutely continuous and its tangent vector lies within  $E$  at a.e. point, and by setting  $\ell(c) = \infty$  otherwise. If  $E$  is integrable, then the topology defined by  $d_\ell$  is none other than the leaf topology. The case of nonintegrable  $E$  is of great interest.

A basic example of the latter structure is provided by the 3-dimensional Heisenberg group  $\mathbb{H}^3$  of matrices of the form

$$\begin{pmatrix} 1 & x & z \\ 0 & 1 & y \\ 0 & 0 & 1 \end{pmatrix},$$

equipped with a left-invariant metric. The quotient of  $\mathbb{H}^3$  by its center  $C$  (isomorphic to  $\mathbb{R}$ ) defines a Riemannian fibration (see [Ber–Gau–Maz], Ch. 1) of  $\mathbb{H}^3$  over the Euclidean plane  $\mathbb{H}^3/C \simeq \mathbb{R}^2$ . The subbundle  $E$  then consists of the horizontal subbundle of this fibration, which coincides with the kernel of the 1-form  $dz - x\,dy$ .

**1.5.** Suppose  $X$  is equipped with a length structure  $\ell$ , and let  $\tilde{\ell}$  be the length structure defined by the metric  $d_\ell$ . The following criterion, which is nothing more than an axiomatic version of the classical properties of the lengths of curves in metric spaces, describes when these two structures are identical.

**1.6. Proposition:** *If, for each interval  $I$ , the function  $\ell$  is lower semicontinuous on  $C(I)$  with respect to the compact-open topology, then  $\ell = \tilde{\ell}$ .*

**Proof.** By 1.3(d), the function  $t \mapsto \ell(f|_{[a,t]})$  is uniformly continuous on  $I = [a, b]$ . For each  $\varepsilon > 0$ , there exists  $\eta > 0$  such that if  $|t - t'| < \eta$ , then  $d_\ell(f(t), f(t')) < \varepsilon$ .

Let  $a = t_0 \leq t_1 \leq \dots \leq t_{n+1} = b$  be a partition of  $I$  having increments no larger than  $\eta$ . For each integer  $i$  between 0 and  $n$ , there exists a map  $g_i$  in  $C([t_i, t_{i+1}])$  having the same values as  $f$  at  $t_i, t_{i+1}$  such that

$$\ell(g_i) \leq d_\ell(f(t_i), f(t_{i+1})) + \varepsilon/n.$$

By juxtaposing the  $g_i$ , we obtain a curve  $h_\varepsilon$  satisfying

$$\ell(h_\varepsilon) = \sum_{i=0}^n \ell(g_i) \leq \sum_{i=0}^n d_\ell(f(t_i), f(t_{i+1})) + \varepsilon \leq \tilde{\ell}(f) + \varepsilon$$

and such that for each  $t \in I$ , we have  $d_\ell(h_\varepsilon(t), f(t)) \leq 3\varepsilon$ .

From the hypothesis that  $\ell$  is lower semicontinuous, it follows that

$$\ell(f) \leq \liminf_{\varepsilon \rightarrow 0} \ell(h_\varepsilon) \leq \tilde{\ell}(f),$$

whereas the opposite inequality is an immediate consequence of the definition of  $\ell$ .

**Remark:** If  $\ell$  is the length structure associated with a metric  $d$ , then the same argument as above shows that  $\ell = \tilde{\ell}$ , using the semicontinuity of length with respect to  $d$  (cf. 1.2 and [Choql], p. 137). In other words, by following the sequence of constructions

$$\begin{array}{ccc} (X, d), \text{ a metric} & \xrightarrow{\quad \text{metric length} \quad} & (X, d_\ell), \text{ a new metric} \\ \text{space} & \longrightarrow & \text{structure } \ell \text{ on } X & \longrightarrow & \text{associated with the} \\ & & & & \text{length structure,} \end{array}$$

we obtain the same length structure. Nevertheless, we again emphasize that  $\ell \neq \tilde{\ell}$  in general.

**1.6<sub>2+</sub>** **Locality of the length structure.** If two length structures agree on some open subsets covering  $X$ , then they are obviously equal. Conversely, if we are given a covering of  $X$  by open subsets  $X_i$  for  $i \in I$ , together with length structures  $\ell_i$  on the  $X_i$  which are compatible on the intersections  $X_i \cap X_j$  for all  $i, j \in I$ , then there obviously exists a (unique) length structure on  $X$  that restricts to  $\ell_i$  on each  $X_i$ . (In other words, the length structures comprise a *sheaf* over  $X$ .) On the other hand, metrics on  $X$  are not local (they form only a presheaf over  $X$ ), but they can be localized as follows: Given a metric  $d$  on  $X$ , we consider all metrics  $d'$  that are *locally majorized* by  $d$ . This means that for each  $x \in X$ , there exists a neighborhood  $Y_x \subset X$  of  $x$  such that  $d|_{Y_x} \geq d'|_{Y_x}$ . Now take the supremum of all these  $d'$  and call it  $d_m$ . (Note that the supremum of a bounded family of metrics is again a metric. In general, this supremum may be infinite at some pairs of points in  $X$ , but otherwise it looks like a metric.) Clearly  $d_m \leq d_\ell$  in any metric space  $(X, d)$ ; if  $(X, d)$  is *complete*, then  $d_m = d_\ell$ , as a trivial argument shows (see Section 1.8 below).

## B. Path metric spaces

**1.7. Definition:** A metric space  $(X, d)$  is a *path metric space* if the distance between each pair of points equals the infimum of the lengths of curves joining the points (i.e., if  $d = d_\ell$ ).

**Examples:** Note that, according to this definition the Euclidean plane is a path metric space, but the plane with a segment removed is *not*.



The  $n$ -sphere  $S^n$  is not a path metric space when equipped with the metric induced by that of  $\mathbb{R}^{n+1}$ , but it *is* a path metric space for the geodesic metric by Proposition 1.6.

Path metric spaces admit the following simple characterization.

**1.8. Theorem:** *The following properties of a metric space  $(X, d)$  are equiv-*

alent:

1. For arbitrary points  $x, y \in X$  and  $\varepsilon > 0$ , there is a  $z$  such that

$$\sup(d(x, z), d(z, y)) \leq \frac{1}{2} d(x, y) + \varepsilon.$$

2. For arbitrary  $x, y \in X$  and  $r_1, r_2 > 0$  with  $r_1 + r_2 \leq d(x, y)$ , we have

$$d(B(x, r_1), B(y, r_2)) \leq d(x, y) - r_1 - r_2,$$

for

$$d(B_1, B_2) = \inf_{\substack{x' \in B_1 \\ y' \in B_2}} d(x', y').$$

Every path metric space has these properties, and conversely, if  $(X, d)$  is complete and satisfies (1) or (2), then it is a path metric space.

**Proof.** Let  $(X, d)$  be a complete metric space satisfying condition (1), and set  $\delta = d(x, y)$ . Given a sequence  $(\varepsilon_k)$  of positive numbers, there is a point  $z_{1/2}$  such that  $\max(d(x, z_{1/2}), d(z_{1/2}, y)) \leq \delta/2 + \varepsilon_1 \delta/2$ , and points  $z_{1/4}, z_{3/4}$  for which each of the distances  $d(x, z_{1/4}), d(z_{1/4}, z_{1/2}), d(z_{1/2}, z_{3/4}), d(z_{3/4}, y)$  are less than

$$1/2(\delta/2 + \varepsilon_1 \delta/2) + \varepsilon_2(\delta/2 + \varepsilon_1 \delta/2), \text{ etc.}$$

By choosing the sequence  $(\varepsilon_k)$  so that  $\sum_k \varepsilon_k < \infty$ , we can define a map  $f$  from the dyadic rationals in  $[0, 1]$  into  $X$  satisfying

$$d\left(f\left(\frac{p}{2^n}\right), f\left(\frac{p+1}{2^n}\right)\right) \leq \frac{\delta}{2^n} \prod_{k=1}^{\infty} (1 + \varepsilon_k).$$

If  $(X, d)$  is complete, then this map extends to the entire interval  $[0, 1]$ . Since we can choose the  $\varepsilon_k$  so that the product  $\prod(1 + \varepsilon_k)$  is arbitrarily close to 1, we obtain curves whose lengths tend to  $\delta = d(x, y)$ , which proves the last assertion.

The implication  $(1) \Rightarrow (2)$  is proven in the same way, whereas  $(2) \Rightarrow (1)$  and the assertion that a path metric space satisfies (1),(2) are trivial.

Path metric spaces enjoy some of the same geometric properties as Riemannian manifolds.

**1.8bis. Property:** If  $(X, d)$  is a path metric space, and if  $f$  is a map of  $X$  into a metric space  $Y$ , then the dilatation of  $f$  obviously equals the supremum of its local dilatation, i.e.,  $\text{dil}(f) = \sup_{x \in X} \text{dil}_x(f)$ . Note that

if  $X$  and  $Y$  are Riemannian manifolds, and if  $f$  is differentiable, then the differential  $Df_x : T_x X \rightarrow T_{f(x)} Y$  satisfies  $\text{dil}_x(f) = \|Df_x\|$ .

**1.8bis<sub>+</sub> Kobayashi metrics.** Let  $\Delta$  be a path metric space and let  $X$  be an arbitrary (say, topological) space with a distinguished set of maps  $f : \Delta \rightarrow X$ . Consider all metrics  $d'$  on  $X$  for which these  $f$  have  $\text{dil}(f) \leq 1$ , i.e., for which the mappings are (nonstrictly) distance decreasing, and define  $d_K$  as the supremum of the metrics  $d'$  on  $X$ . Here, it is convenient to admit *degenerate* metrics  $d'$  (in the sense that  $d'(x, y) = 0$  for perhaps some  $x \neq y$ ), so that  $d_K$  may itself be degenerate. In fact, this  $d_K$  is a (possibly degenerate) path metric by the property above.

In the classical example, due to Kobayashi,  $\Delta$  is the unit open disk equipped with the Poincaré metric (i.e., the hyperbolic plane),  $X$  is a complex analytic space, and the collection of distinguished maps consists of all holomorphic mappings  $\Delta \rightarrow X$ . The usefulness of this metric is based on the *Schwarz lemma* (and its various generalizations), which implies that  $d_K$  is *nondegenerate* for many  $X$ . Such  $X$  are said to be (Kobayashi) *hyperbolic*. For example, the disk  $\Delta$  is itself hyperbolic since  $d_K$  in this case equals the Poincaré metric (following from the fact that every holomorphic map  $\Delta \rightarrow \Delta$  is distance decreasing with respect to the Poincaré metric, a consequence of the classical Schwarz–Ahlfors lemma). The basic features of the Kobayashi metric and hyperbolicity do not depend on the integrability of the implied (almost) complex structure of  $X$  and therefore extend to all *almost complex* manifolds  $X$  (via the theory of pseudo-holomorphic curves in  $X$ , cf. [McD–Sal]). For example, hyperbolicity is stable under small (possibly singular) perturbations of almost complex structures on compact manifolds and (suitably defined) singular almost complex spaces (compare [Kobay], [Brody], [Krug–Over]).

There is also a real analog of Kobayashi hyperbolicity, in which  $X$  is a Riemannian manifold,  $\Delta$  is as above, and the set of distinguished maps consists of all conformal, globally area minimizing mappings  $\Delta \rightarrow X$ . In this case, hyperbolicity of  $X$  is equivalent to  $\delta$ -hyperbolicity (see (e) in 1.19<sub>+</sub> below) under mild restrictions on  $X$ , which are satisfied, for example, if  $X$  is the universal cover of a compact manifold. (In fact,  $X$  does not have to be a manifold here — it can be a rather singular space, e.g., a simplicial polyhedron as in 1.15<sub>+</sub>, see [Gro]<sub>HG</sub>, [Gro]<sub>HMGA</sub>.)

**1.9. Definition:** A *minimizing geodesic* in a path metric space  $(X, d)$  is any curve  $f : I \rightarrow X$  such that  $d(f(t), f(t')) = |t - t'|$  for each  $t, t' \in I$ . A *geodesic* in  $X$  is any curve  $f : I \rightarrow X$  whose restriction to any sufficiently small subinterval in  $I$  is a minimizing geodesic.

In this connection, we have the following :

**Hopf–Rinow theorem.** *If  $(X, d)$  is a complete, locally compact path metric space, then*

1. *Closed balls are compact, or, equivalently, each bounded, closed domain is compact.*
2. *Each pair of points can be joined by a minimizing geodesic.*

Before turning to the proof of the theorem, we observe that if  $(X, d)$  is a complete, locally compact metric space, then there are many noncompact balls for the metric  $d' = \inf(1, d)$ .

**1.11 Compactness of closed balls.** Note that if  $a$  is a point in  $X$ , then the ball  $B(a, r)$  is by hypothesis compact if  $r$  is sufficiently small. We will first show that if  $B(a, r)$  is compact for all  $r$  in an interval  $[0, \rho)$ , then  $B(a, \rho)$  is compact as well.

Let  $(x_n)$  be a sequence of points in  $B(a, \rho)$ . We may suppose that the distances  $d(a, x_n)$  tend to  $\rho$ ; otherwise, there is a ball  $B(a, r)$  with  $r < \rho$  containing infinitely many of the  $x_n$  and thus a limit point of the sequence. Let  $(\varepsilon_p)$  be a sequence of positive real numbers tending to zero. By applying property (2) of Theorem 1.8, we find that for each  $p$ , there exists an integer  $n(p)$  such that for each  $n > n(p)$ , there is a point  $y_n^p$  satisfying

$$y_n^p \in B(a, \rho - 2\varepsilon_p) \quad \text{and} \quad d(x_n, y_n^p) \leq \varepsilon_p.$$

For each  $p$ , the sequence  $(y_n^p)$  lies within a compact set; by a diagonal argument (or since the product of compact sets is compact), it follows that there is a sequence of integers  $(n_k)$  such that the subsequence  $(y_{n_k}^p)$  converges for all  $p$ . The sequence  $(x_{n_k})$ , which is the uniform limit of the  $(y_{n_k}^p)$ , is a Cauchy sequence and therefore converges by completeness of  $X$ .

By the preceding remarks, the supremum of the  $r$  for which  $B(a, r)$  is compact is infinite: if instead it equalled  $\rho < \infty$ , then we could find  $\rho' > \rho$  such that  $B(a, \rho')$  would be compact, by using a finite covering of the sphere  $S(a, \rho)$  by compact balls.

### 1.12. Existence of a minimizing geodesic joining two arbitrary points

We first consider the case when  $X$  is compact.

**Lemma:** *If  $(X, d)$  is a compact path metric space and  $a, b \in X$ , then there exists a curve of length  $d(a, b)$  joining  $a$  and  $b$ .*

**Proof.** It suffices to consider curves  $f: [0, 1] \rightarrow X$  which are parametrized by arc length. From the definition of path metric spaces, it follows that for each positive integer  $n$ , there exists such a curve  $f_n$  joining  $a$  to  $b$  and having length less than  $d(a, b) + 1/n$ . The set of  $f_n$  is therefore equicontinuous, and by Ascoli's theorem, there exists a subsequence  $f_{n_k}$  that converges uniformly to a curve  $f: [0, 1] \rightarrow X$ . Since the length function  $\ell$  is lower semicontinuous, we have

$$\ell(f) \leq \liminf_{k \rightarrow \infty} \ell(f_{n_k}) = d(a, b).$$

In the case of a complete, locally compact, but noncompact path metric space, it suffices to note that the images of the curves  $f_n$  chosen in the preceding paragraph lie within the compact ball  $B(a, 2d(a, b))$ .

**1.13. Remarks:** (a) In the case of Riemannian manifolds, this proof fulfills the promise made in the introduction that use would be made only of the associated length structure.

(b) The equicontinuity argument of Lemma 1.12 also shows that *in a compact path metric space, every free homotopy class is represented by a length-minimizing curve*, and that the minimizing curves are geodesics. Moreover, if  $X$  is a manifold, then for each real  $r$ , *there is only a finite number of homotopy classes represented by curves of length less than  $r$*  (again, it suffices to use Ascoli's theorem and the fact that the homotopy classes are open subsets of  $C^0(S^1, X)$ ; cf. [Dieu], p. 188). These results also hold for homotopy classes of curves based at a point  $x \in X$  and geodesics based at  $x$  (but not necessarily smooth at  $x$ ) and will play a key role, particularly in Chapter 5.

## C. Examples of path metric spaces

**1.14. Riemannian manifolds with boundary and subsets of  $\mathbb{R}^n$  with smooth boundary.** Let  $X$  be a domain in  $\mathbb{R}^n$  with smooth boundary, equipped with the metric and length structure induced by that of  $\mathbb{R}^n$ , and let  $f$  be the identity map

$$(X, \text{induced metric}) \rightarrow (X, \text{induced length metric}).$$

It is easy to see that if the boundary of  $X$  is smooth, then  $\text{dil}_x(f) = 1$  for each  $x \in X$ , and that  $\text{dil}(f) = 1$  if and only if  $X$  is convex.

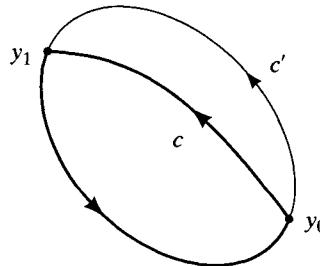
**Distortion<sub>+</sub>:** More generally, let  $X$  be a subset of a path metric space  $A$  and let  $\text{distort}(X)$  denote the dilatation of the identity map  $f: X \rightarrow X$  with respect to the two induced metrics, i.e.,

$$\text{distort}(X) = \sup \frac{(\text{length dist})|_X}{\text{dist}|_X}.$$

Our first observation is the following:

- (a) *Let  $X$  be a compact subset of  $\mathbb{R}^n$ . If  $\text{distort}(X) < \frac{\pi}{2}$  (which means that every two points in  $X$  that lie within a Euclidean distance of  $d$  from one another can be joined by a curve in  $X$  of length  $< d\pi/2$ ), then  $X$  is simply connected.*

**Proof.** To prove this assertion, we argue by contradiction. Suppose  $\pi_1(X) \neq 0$  and let  $\alpha$  be a nontrivial homotopy class in which there exists a curve of minimal length among all homotopically nontrivial loops (the existence of such  $\alpha$  is guaranteed by Remark 1.13(b)). Let  $Y$  be the image of  $c$  and  $g: Y \rightarrow Y$  the identity map of the space  $Y$  with its induced length structure. We claim that  $\text{dil}(g) = \text{dil}(f|_Y)$ .



To prove the claim, let  $y_1, y_0$  be two points of  $Y$  and fix a parametrization of  $Y$  by arc length, i.e., a map  $c: [0, \ell] \rightarrow Y$  such that  $c(0) = y_0 = c(\ell)$  and  $y_1 = c(d)$  for some  $d \in [0, \ell]$  such that  $d \leq \ell - d$ . Then  $c|_{[0,d]}$  is the shortest path joining  $y_0$  to  $y_1$  in  $X$ . Indeed, if there were a strictly shorter path  $c'$  from  $y_0$  to  $y_1$ , then the two loops obtained by adjoining  $c'$  and the two parts of  $c$  defined by the parameters 0 and  $d$  would be strictly shorter than  $c$ . Since their product is homotopic to  $c$ , however, we could conclude that one of the two is not homotopic to 0 in  $X$ , which contradicts the minimality of  $c$ . Since the path  $c|_{[0,d]}$  lies within  $Y$ , it follows that  $d$  is the distance from  $y_0$  to  $y_1$  for the length metrics of  $X$  and  $Y$ , and that

$$\text{dil}_{(y_0, y_1)}(g) = \text{dil}_{(y_0, y_1)}(f).$$

Thus, we have  $\text{dil}(g) < \pi/2$ . Extend  $c$  to a periodic function on  $\mathbb{R}$  and set  $r(s) = d(c(s), c(s + \ell/2))$ , so that the inequality  $r(s) \geq \ell/2 \text{dil}(g)$  holds. Set  $u(s) = (c(s + \ell/2) - c(s))/r(s)$ . The curve  $u$  is differentiable almost everywhere, and its image lies within the unit sphere of  $\mathbb{R}^n$ . Moreover,  $u(s + \ell/2) = -u(s)$ , so that the length of  $u$  is at least  $2\pi$ . Thus,

$$\left\| \frac{du}{ds} \right\|^2 \leq \frac{1}{r(s)^2} \left( 4 - \left( \frac{dr}{ds} \right)^2 \right) \leq \frac{4}{r(s)^2} \leq \left( \frac{4 \text{dil}(g)}{\ell} \right)^2,$$

and so  $\ell(u) \leq 4 \text{dil}(g) < 2\pi$ , which is the desired contradiction.

**Remark:** If  $\text{dil}(d) = \pi/2$ , and if  $X$  is not simply connected, then  $X$  contains a round circle.

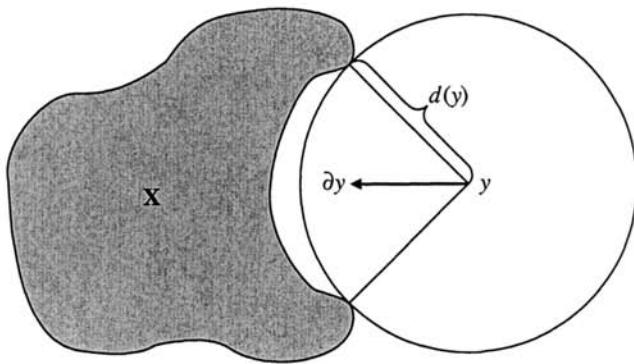
(b) *If  $\text{distort}(X) < \pi/2\sqrt{2}$ , then  $X$  is contractible.*

**Proof<sub>+</sub>**. The idea is to homotopy-retract  $\mathbb{R}^n$  to  $X$  by following the flow of a suitable vector field  $\partial$  which plays the role of  $-\text{grad } d(y)$  for the distance function  $d: y \mapsto \text{dist}(y, X) = \inf_{x \in X} \|y - x\|$ . In general, the function  $d$  is nonsmooth, even on the complement  $\mathbb{R}^n \setminus X$ . Nonsmoothness at a point  $y \in \mathbb{R}^n \setminus X$  is due to the fact that the sphere  $S_y^{n-1}$  at  $y$  of radius  $d(y)$  can meet  $X$  at several points. These points essentially realize the above infimum, since the *open* ball bounded by  $S_y^{n-1}$  does not intersect  $X$ , while the set  $X \cap S_y^{n-1}$  is nonempty and  $d(y) = \|x - y\|$  for all  $x \in X \cap S_y^{n-1}$ . Now we observe that the normal projection  $X \rightarrow S_y^{n-1}$  is distance-decreasing and thus  $(\text{length dist})_X(x_1, x_2) \geq (\text{length dist})_{S_y^{n-1}}(x_1, x_2)$  for all pairs of points in the intersection  $X \cap S_y^{n-1}$ . It follows that the latter distance is bounded by  $\pi d(y)/2$ , and since we assume the *strict* inequality  $\text{distort}(X) < \pi/2\sqrt{2}$ , the distance above is bounded by  $\delta \pi d(y)/2$  for some  $\delta < 1$  independent of  $y$ . Consequently, the intersection  $X \cap S_y^{n-1}$  is *strictly* contained in a hemisphere, or, in other words, *there exists a unit vector  $\partial_y$  at every  $y \in \mathbb{R}^n \setminus X$  such that*

$$\partial_y \|x - y\| \leq -\varepsilon < 0 \quad \text{for all } x \in X \cap S_y^{n-1}, \quad (*)$$

where  $\partial_y \|x - y\|$  denotes the  $\partial_y$ -derivative of the (distance) function  $y \mapsto \|x - y\|$ . In fact, one can take  $\partial_y$  to be the vector which points towards center of the minimal spherical cap in  $S_y^{n-1}$  containing  $X \cap S_y^{n-1}$ , thus obtaining a (Borel) measurable vector field  $y \mapsto \partial_y$  satisfying (\*).

Finally, we can easily smooth this vector field, so that the resulting (now smooth!) unit vector field, say  $y \mapsto \bar{\partial}_y$  on  $\mathbb{R}^n \setminus X$ , satisfies (\*) (possibly with a smaller  $\varepsilon > 0$ ) as well. Clearly, every forward orbit of such a field



converges to a point in  $X$ , and so the flow generated by  $\bar{D}$  eventually retracts  $\mathbb{R}^n$  to  $X$ .

**Remark<sub>+</sub>:** A sharper result is proved in Appendix A, where one allows  $\text{distort}(X) < 1 + \alpha_n$  for some specific  $\alpha_n > 1 - \pi/2\sqrt{2}$ . Furthermore, there are many examples of (necessarily contractible) subsets  $X$  with arbitrarily large (even infinite) distortion for which  $X \cap S_y^{n-1}$  is still strictly contained in an open hemisphere for each  $y \in \mathbb{R}^n \setminus X$  and to which our argument applies. On the other hand, we do not know the precise value of  $\alpha_n$  for which  $\text{distort}(X) < 1 + \alpha_n$  necessarily implies that  $X$  is contractible.

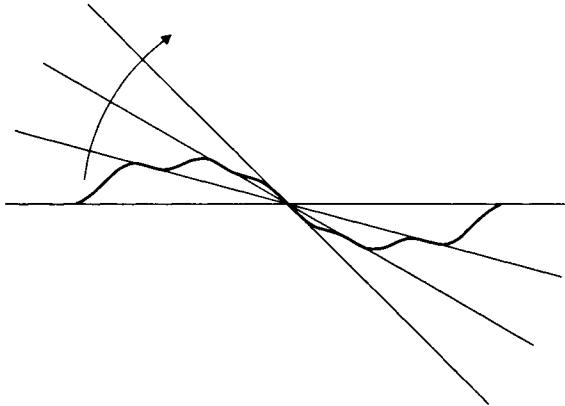
**Exercise<sub>+</sub>:** Construct a closed, convex surface  $X$  in  $\mathbb{R}^3$  with  $\text{distort}(X) < \pi/2$ . (Compare Appendix A.)

**Problem<sub>+</sub>:** Given a topological space  $X$ , evaluate the infimum of all distortions induced by embeddings  $X \rightarrow \mathbb{R}^n$  or of those distortions induced by embeddings which lie in a fixed isotopy class. The first interesting case arises when  $X$  is the circle and we minimize the distortion for  $X$  knotted in  $\mathbb{R}^3$  in a prescribed way (compare [Gro]<sub>HED</sub>, [O'Hara]<sub>EK</sub>).

**Remark<sub>+</sub>:** The geometry of subsets  $X \subset \mathbb{R}^n$  satisfying  $\text{distort}(X) \leq 1 + \alpha_n$  can be rather complicated, even for small  $\alpha_n > 0$ . For example, there are simple smooth arcs in  $\mathbb{R}^2$  with arbitrarily small (i.e. close to 1) distortion which have an arbitrarily large turn of the tangent direction. To see this, consider diffeomorphisms  $T_i: \mathbb{R}^2 \rightarrow \mathbb{R}^2$  with the following properties: Each  $T_i$  fixes the complement of the disk of radius  $2^{-i}$  around the origin and isometrically maps the disk of radius  $2^{-i-1}$  into itself by rotating it by a small angle  $\alpha > 0$ .

Clearly, one can choose the  $T_i$  so that they and their inverses are  $(1 + \varepsilon)$ -

Lipschitz for  $\varepsilon < 10\alpha$ . Since the distortion of such a  $T_i$  is located in the annulus between  $2^{-i}$  and  $2^{-i+1}$ , the diffeomorphism given by the composition  $U_i = T_1 \circ T_2 \circ \dots \circ T_i$  are also  $(1 + \varepsilon)$  Lipschitz along with their inverses  $U_i$ , since the “distortion supports” of the  $T_i$  are mutually disjoint. Note, however, that for large  $i$ , the map  $U_i$  is the identity outside of the unit disk and rotates the  $2^{-i-1}$  disk by the angle  $i\alpha$ , which can be quite large for large  $i$ . Also, the  $U_i$ -image of the unit segment in  $\mathbb{R}^2$  passing through the origin may have arbitrarily large rotation of the tangent direction, while its distortion does not exceed  $1 + \varepsilon$ .



The full richness of this picture becomes apparent in Appendix B<sub>+</sub>.

**Asymptotic distortion<sub>+</sub>.** Define

$$\text{distort}(X; D) = \sup \text{dist}(x_1, x_2),$$

where the supremum ranges over all  $x_1, x_2 \in X \subset A$  with  $\text{dist}_A(x_1, x_2) \geq D$  with respect to the induced length metric, and study the asymptotic behavior of this distortion as  $D \rightarrow \infty$ . For example, if  $X$  is a properly embedded, noncompact submanifold in *hyperbolic space*  $\mathbb{H}^n$ , then either  $\text{distort}(X) < \infty$  or  $\text{distort}(X; D)$  grows *exponentially* as  $D \rightarrow \infty$ . On the other hand, the distortion of every connected subgroup  $X$  of a Lie group  $A$  is *at most* exponential. This is easy to see for  $A = GL_n$  and for algebraic groups in general (see [Gro]AI); the (more difficult) nonalgebraic case was recently settled by Varopoulos (see [Var]).

**1.15<sub>+</sub> Polyhedral metrics.** Assign a length structure to the standard  $n$ -simplex

$$\Delta^n = \{x_0, x_1, \dots, x_n \geq 0 : \sum_{i=0}^n x_i = 1\} \subset \mathbb{R}^{n+1}$$

that is invariant under the automorphisms of  $\Delta^n$  corresponding to permutations of the vertices of  $\Delta^n$  (labelled by the indices  $0, 1, \dots, n$ ). Suppose this is done *coherently* for all  $\Delta^n$ , for  $n = 1, 2, \dots$ , i.e., so that the chosen length structure on  $\Delta^{n-1}$  coincides with the length structure induced by the standard (face) embedding  $\Delta^{n-1} \subset \Delta^n$  from the chosen length structure on  $\Delta^n$ . For example, we can take the Euclidean structure on  $\Delta^n \subset \mathbb{R}^{n+1}$ , or the spherical structure induced by the radial projection  $\Delta^n \rightarrow S^n$ . Furthermore, we can modify the ambient metric in  $\mathbb{R}^{n+1}$ , e.g., by using the  $\ell_1$ -norm  $\|x\|_{\ell_1} = \sum_{i=0}^n |x_i|$ , or we can identify  $\Delta^n$  with the regular simplex of diameter  $d$  in hyperbolic  $n$ -space for a given  $d \in [0, \infty]$ .

Once the length structure on  $\Delta^n$  has been chosen, every simplicial polyhedron  $K$  acquires a unique length structure which restricts to this structure on all of its simplices (compare 1.6 $_{\frac{1}{2}+}$ ). The resulting path metric spaces exhibit an unexpected richness of geometry. Even in the simplest case where  $K$  is a *tree* (i.e., a contractible 1-complex), the picture is not quite trivial (just try to figure out when a 4 point metric space admits an isometric embedding into such a tree). And if we allow infinite-dimensional polyhedra  $K$ , then we will be able to apply metric treatment to arbitrary homotopy types (of spaces) via their (semi-) simplicial models (see 5.42).

**1.15 $_{\frac{1}{2}+}$  Semialgebraic sets.** A subset  $X \subset \mathbb{R}^n$  is called (real) *algebraic* if it is defined via some polynomials  $P_i$ ,  $i = 1, \dots, I$ , on  $\mathbb{R}^n$  as follows:

$$X = \{x \in \mathbb{R}^n : P_i(x) = 0 \text{ for } i = 1, \dots, I\}.$$

We call  $X$  *special semialgebraic* if, in addition to the polynomial equations above, we allow finitely many strict and nonstrict polynomial inequalities:

$$X = \{x \in \mathbb{R}^n : P_i(x) = 0; Q_j(x) \geq 0; R_k(x) > 0\}.$$

The basic measure of the geometric complexity of such  $X$  is the sum of the degrees of these polynomials:

$$D(P_i, Q_j, R_k) = \sum_i \deg(P_i) + \sum_j \deg(Q_j) + \sum_k \deg(R_k),$$

or, more precisely, the infimum  $\text{algdeg}(X)$  of the numbers  $D(P_i, Q_j, R_k)$ , where the  $P_i, Q_j, R_k$  range over all polynomials which represent a given  $X$  as above (the representation of  $X$  by  $P_i, Q_j, R_k$  is highly nonunique. Note, for instance, that  $X$  remains the same when we replace the given polynomials by their cubes  $P_i^3, Q_j^3, R_k^3$ ). Finally, *semialgebraic*  $X$  are defined as a finite union of special semialgebraic subsets.

It is not hard to see that the induced length structure on  $X \subset \mathbb{R}^n$  is rather regular (albeit far from fully understood). In particular, the length

metric induces the same topology on (each connected component of)  $X$  as the induced metric. In fact, if  $X$  is an algebraic curve of degree  $d$ , then it meets each hyperplane in at most  $d$  points, and so the length of the intersection of  $X$  with a ball of radius  $R$  does not exceed  $2Rd$  by the Crofton formula. This gives a rough idea of the length metric on such  $X$  when we recall (the well known fact) that for each  $x \in X$ , there exists  $R > 0$  such that the intersection of  $X$  with the Euclidean  $r$ -ball around  $x$  is connected for all  $r < R$ . (In fact,  $X \cap B(x, r)$  is *contractible for all semialgebraic*  $X$  and  $r \leq R = R(x) > 0$ .) This implies that

$$\text{lengthdist}(x, y) \leq 2d \text{ dist}(x, y)$$

for every  $x \in X$  and all  $y \in X \cap B(x, r)$ . Moreover, by projecting a semialgebraic curve  $X$  onto lines in  $\mathbb{R}^n$  and then isolating “branches” of  $X$ , one can improve the above estimate to

$$\text{lengthdist}(x, y) \leq (1 + \varepsilon) \text{ dist}(x, y), \quad (\leq)_\varepsilon$$

where  $\varepsilon = \varepsilon(x, r) \rightarrow 0$  as  $r \rightarrow 0$ . (Probably  $(\leq)_\varepsilon$  holds for all semialgebraic sets  $X$ .) Note that the convergence  $\varepsilon \rightarrow 0$  might be nonuniform in  $x$ , as is seen in the case when  $X$  consists of two smooth curves which are tangent at a single point. But, one can show that every bounded, connected semialgebraic set  $X$  satisfies

$$\text{lengthdist}(x, y) \leq C \text{ dist}^\alpha(x, y), \quad (\leq)_\alpha$$

for some  $C = C(X)$  and  $\alpha = \alpha(\text{algdeg}(X)) > 0$ . This is weaker than  $(\leq)_\varepsilon$  for individual  $x$ , but it has the advantage of being satisfied by all  $x$  and  $y$ , with  $C$  independent of these points. (See [Gro]Yom, [Gro]SGSS for more information and references about the geometry of semialgebraic sets)

**1.16+ Quotient spaces  $X/\Gamma$ .** If  $(X, d_X)$  is a metric space and  $f: X \rightarrow Y$  is a surjective map, then  $Y$  can be equipped with the *quotient metric*  $d$ , equal to the supremum of those  $d'$  on  $Y$  for which the map  $f$  is (nonstrictly) distance decreasing (i.e., with  $\text{dil}(f) \leq 1$ ). Notice that the metric  $d$  may degenerate (as did the Kobayashi metrics), but if  $Y = X/\Gamma$  for a group  $\Gamma$  that acts *isometrically* on  $X$  and that has *closed* orbits, then  $d$  is nondegenerate. (Here, the distance between the orbits  $y_1 = \Gamma(x_1)$  and  $y_2 = \Gamma(x_2)$  clearly satisfies  $d(y_1, y_2) = \inf_{\gamma \in \Gamma} d(x_1, \gamma(x_2))$ .) If  $d_X$  is a *path* metric, then so is  $d$ , since its construction is local. In fact, the length structure in  $Y$  can sometimes be recaptured (but not always!) by lifting curves  $c$  from  $Y$  to  $X$  and then defining  $\text{length}_Y(c)$  as the infimum of the  $X$ -lengths of all such lifts. Ideally, we would like to have *horizontal* lifts  $\tilde{c}$  of curves  $c$  in  $Y$  to  $X$

so that  $\text{length}_X(\tilde{c}) = \text{length}_Y(c)$ , and this is possible, for example, when  $X$  is a *Riemannian manifold* and  $Y = X/\Gamma$ . Here, we *declare* a smooth curve  $\bar{c}$  in  $X$  to be *horizontal* if it is normal to the orbits of  $\Gamma$  (which is no restriction at all if  $\Gamma$  is discrete) and introduce the length structure in  $Y$  using the projection  $c$  of these horizontal  $\bar{c}$  to  $X$ , where we define

$$\text{length}_Y(c) = \text{length}_X(\bar{c}).$$

Then the metric in  $Y$  associated with this length structure equals the quotient metric  $d$  in  $Y$ , as easily follows from the slice theorem for isometry groups. Note that this  $Y$  is singular unless the action of  $\Gamma$  is free. This remark will play an important role in Chapters 3 and 8.

**1.17+ Covering metrics.** If  $\tilde{X} \rightarrow X$  is a covering map, then length structures, being local, lift from  $X$  to  $\tilde{X}$ , as do path metrics. In fact, every path metric  $d$  on  $X$  lifts to a unique path metric  $\tilde{d}$  for which the covering map is a *local isometry*.

Although the definition of  $\tilde{d}$  is obvious, the actual determination of its essential properties can become insurmountably difficult. For example, if  $X$  is a compact Riemannian manifold or a finite simplicial polyhedron, then all we may care to ask about  $d$  stands clearly before our eyes. But if we pose some seemingly innocuous question about  $\tilde{d}$  on the *universal cover*  $\tilde{X} \rightarrow X$ , e.g., whether  $\tilde{X}$  has finite or infinite diameter, then we encounter an (algorithmically) unsolvable decision problem of finiteness of the fundamental group of  $X$ . Here, the logical complexity of the problem is ingrained in the very definition of the path metric, the infimum of length over *all* curves between given points. This “all” makes the passage length→distance highly non-effective! Thus, complete knowledge about “length” does not immediately translate into comparable information about “distance,” even in such simple cases as a Lie group  $X$  equipped with a left invariant Riemannian metric  $d$ . Here  $d = d_g$  is uniquely determined by the prescription of a positive definite quadratic form  $g$  on a single tangent space,  $T_e X$ , but evaluating  $d_g(x_1, x_2)$  for given  $x_1$  and  $x_2$  may be difficult. (To see the point, take  $X = GL_n \mathbb{R} \subset \mathbb{R}^{n^2}$  and measure the  $d_g$ -distance between the matrices  $\text{id}$  and  $-\text{id}$  in terms of  $g$  on  $T_{\text{id}} X = \mathbb{R}^{n^2}$ , or try to estimate the diameter of  $X = (SO(n), d_g)$  in terms of  $g$ .)

**1.18. Carnot–Caratheodory metrics associated with a tangent subbundle of a Riemannian manifold.** One can show that the length structure associated with a completely nonintegrable subbundle (cf. 1.4(e)) — as in the case of the Heisenberg group — gives rise to a distance on  $V$  that induces the same topology but radically alters the metric properties (e.g., Hausdorff dimension, etc.) of  $V$ .

**1.19<sub>+</sub> Curvature.** It is hardly possible to find a convincing definition of the curvature (tensor) for an arbitrary metric space  $X$ , but one can distinguish certain classes of metric spaces corresponding to Riemannian manifolds with curvatures of a given type. This can be done, for example, by imposing inequalities between mutual distances of finite configurations of points in  $X$ . More precisely, let  $M_r$  denote the space of positive symmetric  $r \times r$  matrices, and let  $K_r(X) \subset M_r$  be the subset realizable by the distances among  $r$ -tuples of points in  $X$ . Thus,  $(m_{ij}) \in K_r(X)$  if and only if there exist points  $x_1, \dots, x_r$  in  $X$ , such that  $\text{dist}(x_i, x_j) = m_{ij}$ , for  $i, j = 1, \dots, r$ . Then every subset  $\mathcal{K} \subset M_r$  defines the (global)  $\mathcal{K}$ -curvature class, which consists of the spaces  $X$  with  $K_r(X) \subset \mathcal{K}$ , and the local  $\mathcal{K}$ -curvature class, where each point  $x \in X$  is required to admit a neighborhood  $U$  with  $K_r(U) \subset \mathcal{K}$ . In this setting, we have the basic

**Curvature problem:** Given  $\mathcal{K} \subset M_r$ , describe the spaces  $X$  in the (local or global)  $\mathcal{K}$ -curvature class.

In general, a  $\mathcal{K}$ -condition on  $X$  does not seem to lead to an interesting theory unless one exercises good judgement in choosing the set  $\mathcal{K}$ . Geometers usually start with some standard (model) space  $Y$  (or with a family of such spaces) and take  $\mathcal{K} = K_r(Y)$  (or the union of these for a given family of spaces  $Y$ ). If one is willing to sacrifice the combinatorial aspect of the problem, then the phenomena associated with discrete spaces can be ruled out by imposing various connectivity restrictions on  $X$ , such as local path connectedness, local contractability, *controlled contractability*, etc. In particular, one can require  $X$  to be a *path metric* space, in which case one can go amazingly far with a judiciously chosen  $\mathcal{K}$ . But it is difficult to decide by looking at a given  $\mathcal{K}$  whether the corresponding  $\mathcal{K}$ -class is “interesting.” For instance, when does there exist a *path metric* space  $X$  with  $K_r(X) = \mathcal{K}$  for a given  $\mathcal{K} \subset M_r$ ?

**Examples:** (a) If  $X$  is compact and connected, then (obviously) the only information contained in  $K_2(X)$  is the *diameter* of  $X$ , i.e.,  $\sup \text{dist}(x_1, x_2)$ , where the supremum ranges over all  $x_1, x_2 \in X$ .

(b) If  $r = 3$ , then for any metric space  $X$ , the *triangle inequality* requires  $K_3(X)$  to lie within the subset  $\text{Tri} \subset M_3$  consisting of matrices  $(m_{ij})$  that satisfy  $m_{ij} \leq m_{ik} + m_{kj}$  for all  $i, j, k$  running through 1, 2, 3. It seems that most *path metric* spaces  $X$  with *infinite* diameter satisfy  $K_3(X) = \text{Tri}$  (with some notable exceptions such as  $X = \mathbb{R}$  or  $\mathbb{R} \times \text{compact}$ ), but I do not know a good criterion that guarantees this property. For example, all *uniformly contractible* manifolds  $X$  of dimension  $\geq 2$  have large  $K_3(X)$ , probably always equal to  $\text{Tri}$ .

(c) The curvature story starts (and essentially ends, in the present state of the art) with  $r = 4$ . For example,  $K_4$  characterizes Euclidean spaces as follows:

*If a complete path metric space  $X$  has  $K_4(X) \subset K_4(\mathbb{R}^2)$ , then it is isometric to a convex subset in  $\mathbb{R}^2$ . If  $K_4(X) \subset K_4(\mathbb{R}^3)$ , then  $X$  is isometric to a convex subset in a Hilbert space.*

The proof is straightforward and easily extends to complete simply connected spaces  $Y$  with constant curvature in place of  $\mathbb{R}^3$  (see [Rinow] §41). However, a similar characterization has not been worked out for other Riemannian *symmetric spaces*  $Y$ , where one expects every complete path metric space  $X$  with  $K_r(X) \subset K_r(Y)$  for some (sufficiently large)  $r = r(Y)$  to be (isometric to) a convex subset in another (possibly infinite dimensional) symmetric space  $Y'$  that naturally extends the geometry of  $Y$  (as, for example, the Grassmannian manifold  $Gr_k(\mathbb{R}^\infty)$  extends  $Gr_k(\mathbb{R}^n)$ ). On the other hand, it is easy to see that (convex subsets in) normed vector spaces are characterized by  $K_5$ , since the homogeneity of a norm is a five point property.

(d) *Alexandrov spaces with  $K \geq 0$ :* One could define this class by taking the union of  $K_4(Y) \subset M_4$  for all *convex* complete surfaces  $Y \subset \mathbb{R}^3$  equipped with their induced path metrics. Customarily, however, one uses a somewhat larger  $\mathcal{K}(\geq 0) \subset M_4$ , where the  $\mathcal{K}$ -positivity condition is felt only by those quadruples of points  $\{x_i\} \subset X$ ,  $i = 1, \dots, 4$ , with the property that  $x_4$  lies between  $x_2$  and  $x_3$ , i.e.,  $x_4$  satisfies

$$\text{dist}(x_4, x_2) + \text{dist}(x_4, x_3) = \text{dist}(x_2, x_3). \quad (\Delta)$$

In other words, one defines  $K \geq 0$  by requiring that every 1-Lipschitz map  $f : \{x_1, x_2, x_3\} \rightarrow \mathbb{R}^2$  extend to a 1-Lipschitz map  $\{x_1, x_2, x_3, x_4\} \rightarrow \mathbb{R}^2$  for all quadruples  $\{x_i\}$  in  $X$  satisfying  $(\Delta)$ , where “1-Lipschitz” means  $\text{dil}(f) \leq 1$  (see [Alex], [Rinow]). The resulting relation  $\mathcal{K}(\geq 0) \subset M_4$ , called the *Alexandrov–Topogonov comparison inequality* for  $K \geq 0$ , is quite resilient, e.g., *locally*  $K \geq 0$  *implies globally*  $K \geq 0$  (the proof is nontrivial, see [Top], [Bu–Gr–Per]), isometric quotients  $X/\Gamma$  inherit  $K \geq 0$  from  $X$  (this is straightforward), etc., and thus leads to a full-fledged geometric theory without any regularity assumptions on  $X$  (see [Per]SCBB and the references therein).

The Alexandrov–Topogonov inequality can be thought of as a kind of concavity condition on the distance function  $x \mapsto \text{dist}(x_0, x)$  that rules out, for example, all non-Euclidean normed spaces (see [Rinow], p. 33). These,

however, reside within a larger class of path metric spaces  $X$  having a less stringent concavity condition on  $\text{dist}$ . This condition can be described, for example, by requiring that *inward equidistant deformations preserve convexity of hypersurfaces in  $X$* . However, the corresponding theory (starting from the  $K_5$  or  $K_6$  characterization of this property) has not yet been developed.

The  $K \geq 0$  theory generalizes to  $K \geq \kappa$  for given  $\kappa \in \mathbb{R}$ , but other differential geometric curvature positivity conditions have not been extended to singular spaces so far. One might expect that the positivity of the curvature operator and that of the complexified sectional curvature (especially on the isotropic planes) admit  $K_r$  renditions with some not very large  $r$ . On the other hand, the curvature classes  $\text{Ricci} \geq 0$  and  $\text{Sc} \geq 0$  lie beyond the reach of the  $K_r$  language. (See [Gro]sign, [Gro]PCMD for a survey of various positive curvatures; also see Chapters 5 and 8 of this book.)

(e) *Alexandrov spaces with  $K \leq 0$ :* These spaces are defined via a suitable  $\mathcal{K}(\leq 0) \subset M_4$  that expresses the Cartan–Alexandrov–Toponogov comparison inequality for  $K \leq 0$ . (Here, the test spaces  $Y$  are convex space-like surfaces in the light cone of the Lorentz  $(++-)$ -space.) The singular path spaces with  $K \leq 0$  (also called CAT(0)-spaces) are by far more numerous than those with  $K \geq 0$ . For example, simplicial (as well as nonsimplicial) trees equipped with length metrics and cartesian products of these spaces have  $K \leq 0$ . In fact, there are plenty of polyhedra with  $K \leq 0$  locally at each point, and in practice, the inequality  $K \leq 0$  can be confirmed by an elementary combinatorial argument. On the other hand, the local condition  $K \leq 0$  implies strong global properties of  $X$ , such as its *asphericity* (a nice property that is hard to prove using traditional topology). In fact, those polyhedra with  $K \leq 0$  are the core of the geometro-combinatorial approach to infinite groups initiated by Dehn at the turn of the century.

Following Busemann [Busemann], one can extend the notion  $K \leq 0$  to encompass normed linear spaces. The enlarged class is distinguished by the (local) convexity of the distance function,  $x \mapsto \text{dist}(x_0, x)$  on every geodesic segment in  $X$ , or by the property that the convexity of hypersurfaces is preserved under outward equidistant deformations (compare [Gro]HMGA, [E–H–S]).

Another notion (generalizing  $K \leq -\kappa < 0$ , rather than  $K \leq 0$ ) is as follows: Consider all simplicial trees  $Y$  and let  $\text{Tre} \subset M_4$  be the union of  $K_4(Y)$  over all trees  $Y$ . Then take the  $\delta$ -neighborhood  $\text{Tre}_\delta \subset M_4$  of  $\text{Tre}$  for some  $\delta > 0$  (defined with respect to the obvious Euclidean metric in  $M_4$ ) and introduce  $\delta$ -hyperbolic spaces  $X$  as those with  $K_4(X) \subset \text{Tre}_\delta$ . Here, the

essential geometry appears at large scales  $\gg \delta$ , where the behavior of  $\delta$ -hyperbolic spaces is indistinguishable from those with  $K < 0$  (see [Gro]<sub>HG</sub>).

The traditional definition of  $\mathcal{K}(\leq 0) \subset M_4$  is dual to that for given  $\mathcal{K}(\geq 0)$  since it involves the extendability of 1-Lipschitz maps *from*  $\mathbb{R}^2$  *into*  $X$ . Namely, for each quadruple  $\{x_i\} \subset \mathbb{R}^2$  satisfying equation  $(\Delta)$  in (d) above, every 1-Lipschitz map  $\{x_1, x_2, x_3\} \rightarrow X$  should extend to a 1-Lipschitz map  $\{x_i\} \rightarrow X$ ,  $i = 1, \dots, 4$ .

**Exercise:** Let  $X_+$  satisfy the Alexandrov–Topogonov condition  $K \leq 0$ , and let  $Z \subset X_+$  be the union of the minimizing geodesic segments whose ends comprise a three point subset  $\{x_1, x_2, x_3\} \subset X_+$ . Show that every 1-Lipschitz map  $\{x_1, x_2, x_3\} \rightarrow X$  admits a 1-Lipschitz extension to  $Z$ .

**Kirschbraun–Lang–Schroeder<sup>1</sup> Theorem:** *Let  $X_+$  and  $X_-$  be path metric spaces having  $K \geq 0$  and  $K \leq 0$  respectively in the Alexandrov sense. Then, every 1-Lipschitz map  $X'_+ \rightarrow X_-$  for  $X'_+ \subset X_+$  admits a 1-Lipschitz extension to all of  $X_+$ .*

If  $X_+ = X_- = \mathbb{R}^n$ , this is a classical result (see [Kirsz], [Fed]<sub>GMT</sub>, [Gro]<sub>MV</sub>), while the general case is quite recent (see [Lan–Sch], where the authors treat the case when  $K(X_+) \geq \kappa \geq K(X_-)$  for all  $\kappa \in \mathbb{R}$ ). Notice that the Euclidean (and the spherical) case of this theorem follows from monotonicity of the volume of intersections of balls in  $\mathbb{R}^n$ , i.e.,  $\text{vol}(B(x_0, r_0) \cap B(x_1, r_1) \cap \dots \cap B(x_n, r_n))$  is monotone decreasing in the distances  $\|x_i - x_j\|$  between the centers of the balls (which was probably known in antiquity). Also observe the following equivalent version of the Kirschbraun theorem.

(\*) *Let  $f: A \rightarrow S^n$  be a  $\lambda$ -Lipschitz map from an arbitrary subset  $A \subset S^n$  where  $\lambda < 1$ . Then  $f(A)$  is strictly contained in a hemisphere of diameter  $\leq \pi - \varepsilon < \pi$ . (If  $\lambda = 1$  and  $f(A)$  is not contained in a hemisphere, then  $f$  is isometric.)*

**Exercises:** Prove the monotonicity claim above and derive Kirschbraun's theorem from it. Derive (\*) from Kirschbraun's theorem, and conversely show that (\*) implies Kirschbraun's theorem by studying optimal  $\lambda$ -Lipschitz extensions of 1-Lipschitz (partially defined) maps with minimal possible  $\lambda$ . (A reader versed in  $K \geq, \leq 0$  geometry may notice that the Lang–Schroeder

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<sup>1</sup>When I met Petrunin in Spring 96, I asked him whether the Kirschbraun theorem extended to Alexandrov spaces. He responded with “yes, for  $\dim < \infty$ ,” hardly hiding his surprise at my inability to furnish a proof by myself. The next day, I found the preprint by Lang and Schroeder with a complete proof of the most general case, and similar ideas were communicated to me somewhat earlier by Branka Pavlovic.

theorem for (smooth!) Riemannian manifolds also follows from  $(\star)$  via the study of optimal  $\lambda$ -Lipschitz maps).

**Remark:** It is unclear which spaces  $Y$  (say with  $K(Y) \leq 0$ ) admit Lipschitz extensions of maps from  $A \rightarrow Y$  to  $X$  for arbitrary metric spaces  $X$  and subsets  $A \subset X$ , where the implied Lipschitz constant of the extension  $X \rightarrow Y$  is allowed to be bigger than that for the original map  $A \rightarrow Y$ . It is rather obvious that  $Y = \mathbb{R}$  has this property (with  $\text{Lip}|_{\mathbb{R}} = \text{Lip}|_A$ ), and consequently this is true for  $\mathbb{R}^n$  (with  $\text{Lip}|_{\mathbb{R}^n} \leq \delta_n \text{Lip}|_A$ ). The same applies to trees (in place of  $\mathbb{R}$ ) and their products. The question is open, however, in the case of the hyperbolic plane,<sup>2</sup> for example (see [Ball] for some results in this direction).

(f) Finally, we mention the possibility of having  $\mathcal{K}_x \subset M_r$  depend on  $x \in X$  and then consider the (variable) local  $\mathcal{K}_x$ -curvature class at each  $x \in X$ . This notion captures, for example, the idea of *local pinching*, which requires that the sectional curvatures of  $X$  at each point  $x$  be pinched between  $K(x)$  and  $\kappa K(x)$ , for some positive (or negative) functions  $K(x)$  on  $X$  and a local pinching constant  $\kappa > 0$ . (This also seems to be the appropriate framework for the  $K_r$ -rendition of the positivity of the curvature operator and the complexified sectional curvatures mentioned earlier).

## D. Arc-wise isometries

**1.20.** The requirements for a map to be an isometry or even local isometry are too stringent to provide a sufficiently rich class of morphisms for path metric spaces. For example, any Riemannian  $n$ -manifold that is locally isometric to  $\mathbb{R}^n$  must be flat. A more flexible notion is the following.

**1.21. Definition:** An *arc-wise isometry* of path metric spaces  $X, Y$  is a map  $f: X \rightarrow Y$  such that  $\ell(f \circ c) = \ell(c)$  for each Lipschitz curve  $c: I \rightarrow X$  of  $X$ .

### Examples:

- (1) Every closed, piecewise  $C^1$  curve admits an arc-wise isometric mapping into  $\mathbb{R}$ .

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<sup>2</sup>This was recently settled by Branka Pavlovic.

- (2) Every flat manifold of dimension  $n < 5$  admits an arc-wise isometry into  $\mathbb{R}^n$  that is additionally piecewise linear (see [Zalg]). The question is open for  $n \geq 5$ .
- (3) An intuitively plausible property, such as the nonexistence of arc-wise isometries from  $X$  to  $Y$  when  $\dim(X) > \dim(Y)$ , is trivial to prove for  $C^1$  maps but less transparent in general. The proof requires Rademacher's theorem (cf. [Fed]GMT 3.1.6), which states that Lipschitz mappings are differentiable almost everywhere.

We end this chapter with a few results obtained using the methods of Nash and Kuiper.

**1.22.** *If  $X, Y$  are Riemannian manifolds with  $\dim(Y) \geq \dim(X)$ , then there exists an arc-wise isometry from  $X$  into  $Y$ .*

In particular, incredible as it seems, every  $n$ -dimensional Riemannian manifold  $X$  admits an arc-wise isometry  $X \rightarrow \mathbb{R}^n$ . Of course, such mappings will not be  $C^1$  in general!

**1.23 An approximation problem.** Given a Lipschitz mapping  $f_0: X \rightarrow Y$  and  $\varepsilon > 0$ , does there exist an arc-wise isometry  $f_\varepsilon: X \rightarrow Y$  such that

$$d(f_0, f_\varepsilon) = \sup_{x \in X} d(f_0(x), f_\varepsilon(x)) \leq \varepsilon?$$

Evidently, we must have  $\text{dil}(f_0) \leq 1$ .

**1.24. Definition:** A mapping  $f$  between path metric spaces is called *short* if  $\text{dil}(f) \leq 1$  and *strictly short* if  $\text{dil}(f) < 1$ .

**1.25. Theorem (cf. [Gro]PDR):** *If  $X, Y$  are Riemannian manifolds with  $\dim(Y) \leq \dim(X)$ , and if  $f$  is a strictly short mapping from  $X$  into  $Y$ , then the approximation problem has a positive solution.*

This brings us back to the basic problem of the existence of a homotopy of a given continuous map to a short map which is addressed in the following chapter.

**1.25<sub>2+</sub>**. If one feels disgusted by the spineless flexibility of arc-wise isometric maps, then some rigidifying conditions can be added so that the remaining mappings  $f$  in question have no *folds*. (The construction underlying the proof of 1.25 uses multiply folded maps  $X \rightarrow Y$ .) For example, one may insist that  $f: X \rightarrow Y$  be *open* (i.e., that  $f$  map open subsets of  $X$  onto open subsets of  $Y$ ), which is quite a strong assumption for Lipschitz

(and especially arc-wise isometric) maps. Secondly, if  $X$  and  $Y$  are oriented manifolds of the same dimension, then one may require the *local degree* of  $f$  to be positive. In the present setting, this means (usually one uses a stronger condition  $\text{locdeg}_x > 0$ ,  $x \in X$ ) that whenever  $f$  properly maps some open subset  $U \subset X$  onto a subset  $V \subset Y$ , the degree of  $f: U \rightarrow V$  as defined in 2.A is  $> 0$ . Thirdly, one may express the same idea by requiring that the inequality  $\text{Jacobian}(f)_x > 0$  holds for almost all points  $x \in X$  (which makes sense for Lipschitz maps). Finally, one can introduce *co-Lipschitz* maps (compare [B–J–L–P–S] as follows: Let

$$\text{codil}(f) = \sup_{y_1, y_2} \frac{\text{dist}_H(f^{-1}(y_1), f^{-1}(y_2))}{\text{dist}(y_1, y_2)},$$

where  $(y_1, y_2)$  runs over all pairs of distinct points in  $Y$  and  $\text{dist}_H$  denotes the Hausdorff distance (see Section 3.B). If  $\text{codil}(f) \leq \lambda$ , then  $f$  is called  $\lambda$ -*co Lipschitz*. The quotient map  $X \rightarrow Y = X/\Gamma$  for a proper isometry group  $\Gamma$  acting on  $X$  is 1-co-Lipschitz (as well as 1-Lipschitz), for example.

Next, consider the  $R$ -balls  $B_x(R)$  in  $X$  around some point  $x \in X$  and let  $r$  be the radius of the maximal ball in  $Y$  centered at  $f(x)$  and contained in the image  $f(B_x(R)) \subset Y$ . We define

$$\text{codil}_x(f) = \limsup_{R \rightarrow 0} \frac{R}{r}$$

and observe that if  $Y$  is a *path*-metric space and  $X$  is *locally compact* (which can often be relaxed), then

$$\text{codil}(f) = \sup_{x \in X} \text{codil}_x(f).$$

In fact, if  $\text{codil}_x(f) \leq c < \infty$ , then every path  $p: [0, 1] \rightarrow Y$  can be covered by a path  $\tilde{p}: [0, 1] \rightarrow Y$  issuing from a given point  $y \in Y$  over  $p(0) \in X$ . Furthermore, if  $p$  is 1-Lipschitz, then  $\tilde{p}$  can be chosen to be  $c$ -Lipschitz.

### Exercises:

- (a) Show that if  $X$  is complete and  $f: X \rightarrow Y$  is co-Lipschitz, then  $Y$  is also complete.
- (b) Study the following implications between the preceding four conditions for Lipschitz maps between suitably oriented equidimensional Riemannian manifolds:

$$\text{co-Lipschitz} \Rightarrow \text{Jacob} \geq 0 \Leftrightarrow \text{locdeg} \geq 0 \Rightarrow \text{open}.$$

- (c) Decide which of these four conditions ensure that *arc-wise isometric* maps are local isometries. (I did not solve (b) and (c) myself, but I have prepared a good excuse for this.)
- (d) Compare “Lipschitz + co-Lipschitz” with quasiregular maps (see Section 6.A).

**1.26<sub>+</sub> Historical and terminological remarks.** The idea of length structures and path metric spaces goes back at least as far as Gauss, who studied how the bending of surfaces in  $\mathbb{R}^3$  distorts the induced metric but preserves the length structure. In classical geometry, one distinguishes the induced path metric with the name *inner metric*, and the word “inner” is often used for general length spaces as well. Traditionally, geometers were most interested in those “inner metric spaces” that are similar to Riemannian manifolds, and much effort was spent trying to identify and study such spaces with inner (i.e., path) metrics (see [Busemann], [Rinow], [Alex], [Alex-Zalg]).

In this book, we emphasize a different point of view, in which the Riemannian idea is stretched to its limits in order to capture such non-Riemannian beasts as Carnot–Caratheodory spaces (also called “nonholonomic spaces” and “sub-Riemannian” or “subelliptic” manifolds) and trees with infinite branching at every (!) point. In fact, one should not even restrict attention to the length structure, especially if one is attracted by *fractal spaces* (one can also play around with area instead of length, as inspired by symplectic geometry, string theory, and/or the area isoperimetric inequalities in geometric group theory).

Finally, we call the reader’s attention to the paper [Bing], where it is shown that *every compact, connected and locally connected metrizable space admits a path metric*.

# Chapter 2

## Degree and Dilatation

### A. Topological review

Throughout this chapter,  $M$  and  $N$  will denote connected, oriented,  $C^\infty$  manifolds having the same dimension  $n$ . Additionally,  $M$  is assumed to be compact and without boundary.

**2.1. Proposition:** *Let  $f: M \rightarrow N$  be a  $C^\infty$  map, so that there exist regular values of  $f$ , i.e.,  $y \in N$  such that for each  $x \in f^{-1}(y)$  the differential  $Df_x$  has rank  $n$ . For each such  $y \in N$ , the set  $f^{-1}(y)$  is finite, and if we set  $o(x) = 1$  if  $Df_x$  preserves orientation and  $o(x) = -1$  otherwise, then the number*

$$\deg(f, y) = \sum_{x \in f^{-1}(y)} o(x)$$

*does not depend on the regular value  $y$ .*

(See [Milnor]TDV or [Berger]Cours, Ch. 7).

**2.2. Definition:** The *degree*  $\deg(f)$  of a smooth map  $f: M \rightarrow N$  is the number  $\deg(f, y)$ , for any regular value  $y$  of  $f$ .

**2.3. Proposition (see [Milnor]TDV):** *If  $f, g: M \rightarrow N$  are homotopic, then  $\deg(f) = \deg(g)$ .*

**2.4. Definition:** If  $f: M \rightarrow N$  is continuous, then the degree of  $f$  is defined as the degree of any smooth map homotopic to  $f$ .

**2.5. Remark:** If some  $y \in N$  does not lie in the image of a continuous map  $f: M \rightarrow N$ , then  $\deg(f) = 0$ . Note that if  $g$  is smooth and sufficiently

approximates  $f$ , then  $g$  is homotopic to  $f$ , and  $y$  does not lie in the image of  $g$ . Thus,  $y$  is a regular value of  $g$ , and  $\deg(f) = \deg(g) = \deg(g, y) = 0$ .

**2.6. Proposition:** *The integration of  $n$ -forms defines an isomorphism  $H^n(M; \mathbb{R}) \rightarrow \mathbb{R}$ . Moreover, the condition that  $\int_M \omega = 1$  determines a unique class  $\omega_M \in H^n(M; \mathbb{R})$ ; similarly, if  $N$  is compact, there exists a corresponding class  $\omega_N \in H^n(N; \mathbb{R})$ . If  $f : M \rightarrow N$  is continuous, then  $f^*\omega_N$  is proportional to  $\omega_M$ , and the proportionality constant equals the degree of  $f$  defined above. (See [Massey] and [Godb], p. 212).*

**2.7. Remark:** If  $M$  is a compact, oriented Riemannian manifold, then its *volume form* is defined as the unique differential  $n$ -form  $\nu_M$ , which for every  $x \in M$  has value 1 on each oriented, orthonormal frame in  $T_x M$ . The *volume* of  $M$  equals the integral  $\text{vol}(M) = \int_M \nu_M$ . If  $N$  is another compact, oriented Riemannian manifold with volume form  $\nu_N$ , and  $f : M \rightarrow N$  is smooth, then  $\deg(f) = (\text{vol}(N))^{-1} \int_M f^* \nu_N$ . At each point  $m \in M$ , the skew-symmetric  $n$ -form  $f^* \nu_N$  is proportional to  $\nu_M$  by a factor known as the *Jacobian* of  $f$  at the point  $m$ , denoted  $J(f, m)$ . If  $f$  is a diffeomorphism from a subset  $A$  of  $M$  onto a subset  $B$  of  $N$ , then by the change-of-variables formula, we have

$$\int_A f^* \nu_N = \int_A J(f, m) \nu_M = \int_B \nu_N = \text{vol}(B),$$

so that we are justified in setting

$$\text{vol}(f|_A) \stackrel{\text{def}}{=} \int_A f^* \nu_N,$$

even if  $f$  is not a diffeomorphism. In this notation, we have

$$\deg(f) = \text{vol}(f|_M) / \text{vol}(N),$$

where

$$\text{vol}(f) \stackrel{\text{def}}{=} \text{vol}(f|_M).$$

In general, the degree of a map from  $M$  to  $N$  does not completely determine its homotopy class. For example, the mapping  $S^1 \times S^1 \rightarrow S^1 \times S^1$  given by  $(x, y) \mapsto (1, y)$  is not surjective and therefore has zero degree, although the map is not homotopic to 0. Homotopy classes of mappings into spheres, however, are determined by their degree (see [Milnor]TDV, p. 51).

**2.8. Theorem (H. Hopf):** *If  $M$  is a compact, oriented  $n$ -manifold, then two mappings  $M \rightarrow S^n$  are homotopic if and only if they have the same degree.*

## 2.8 $\frac{1}{2}$ + Remarks about degree.

(a) The pointwise degree  $\deg(f, y)$  can also be defined for open and/or disconnected manifolds  $M$  and  $N$ ; all one needs is the finiteness of the pullback  $f^{-1}(y) \subset M$ . This finiteness condition is (obviously) satisfied for regular values  $y$  of *proper* maps  $f$ , i.e., those  $f$  for which  $f^{-1}(Y) \subset M$  is *compact for all compact subsets*  $Y \subset N$  (when  $M$  and  $N$  are allowed to have boundaries  $\partial M, \partial N$ , respectively, the definition of properness usually includes the requirement that  $f(\partial M) \subset \partial N$ ). If  $f$  is proper, then  $\deg(f, y)$  is locally constant on each connected component of  $N$ . In particular,  $\deg(f, y)$  is independent of  $y$  if  $N$  is connected, in which case it is regarded as  $\deg(f)$ . This number does not change under homotopies of proper maps and therefore extends to all *continuous proper maps*  $f: M \rightarrow N$  (compare [Milnor]TDV). If  $M$  is an open connected manifold without boundary, then *the degree of proper maps*  $f: M \rightarrow \mathbb{R}^n$ , denoted  $f \mapsto \deg(f) \in \mathbb{Z}$ , establishes a bijection between the homotopy classes of such maps and  $\mathbb{Z}$ , provided that  $n \geq 2$ , by a (trivial) modification of Hopf's theorem. (If  $n = 1$ , then every proper map  $M \rightarrow \mathbb{R}$  has degree  $\pm 1$  for connected  $M$ , which must be homeomorphic to  $\mathbb{R}$ .)

(b) The notion of degree extends to certain nonproper maps  $f: M \rightarrow N$  such as:

- (i) Maps  $f$  that are constant at infinity and on  $\partial M$ , i.e., constant outside a compact subset  $K \subset \text{Int}(M)$ .
- (ii) If  $\dim(M) = \dim(N) \geq 2$ , one can also allow maps  $M \rightarrow N$  which are *locally constant* outside some compact subset  $K \subset \text{Int}(M)$ .
- (iii) Maps  $f$  which send  $\text{Int}(M) \setminus K$  onto a subset of topological codimension  $\geq 2$  in  $N$ , i.e., those having  $\text{rank}(f|_{\partial M}) < \dim \partial M$  for compact  $M$ .

In all of these cases,  $\deg(f)$  is homotopy invariant and is defined for the continuous maps satisfying (i), (ii), or (iii). Such maps also satisfy the conclusion of Hopf's theorem. For example, if  $M$  is compact and connected, then the homotopy classes of maps  $f: (M, \partial M) \rightarrow (S^n, s_0)$  bijectively correspond with  $\mathbb{Z}$  via  $f \mapsto \deg(f)$ .

(c) Let  $N$  be a Riemannian manifold with finite total volume,  $\text{vol}(N) < \infty$ , and let  $f: M \rightarrow N$  be a smooth map with

$$|\text{vol}|(f) \stackrel{\text{def}}{=} \int_M f^*(|\nu_N|) < \infty,$$

(where  $f^*(|\nu_N|) = |Jf|\nu_M$  for *Riemannian manifolds*  $M$ , and where  $\nu_M$ ,  $\nu_N$  denote the oriented Riemannian volume forms). Then one can define

$$\deg^*(f) = \frac{\text{vol}(f)}{\text{vol}(N)},$$

where we recall that

$$\text{vol}(f) \stackrel{\text{def}}{=} \text{vol}(f|_M) \stackrel{\text{def}}{=} \int_M f^* \nu_N.$$

It is easy to show that this degree can be obtained by integrating the point degree over  $N$ , i.e.,

$$\deg^*(f) = \int_N \deg(f, y) \nu_N,$$

where in fact the integration is taken over the set of regular values of  $f$ , which has full measure in  $N$ . Thus, this  $\deg^*(f)$  coincides with the topological (homotopy invariant) degree  $\deg(f)$  whenever both make sense.

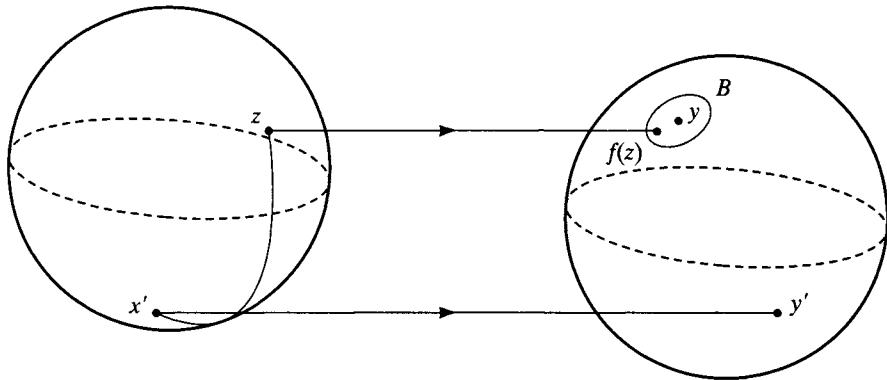
## B. Elementary properties of dilatations for spheres

*Given two path metric spaces  $V, W$ , what can be said about the space of mappings from  $V$  into  $W$  having dilatation less than or equal to a given number  $D$ ? In particular, does there exist such a mapping in each homotopy class? This is a considerable question, which will occupy us in this chapter as well as in Chapter 7. When  $D$  is small, few homotopy classes are represented by such maps; for example, if  $V, W$  are spheres equipped with their standard metrics (i.e., that of the unit sphere in Euclidean space), then we have*

**2.9. Proposition:** *If a map  $f: S^n \rightarrow S^n$  has dilatation strictly less than 2, then the degree of  $f$  equals 1, 0, or -1 (cf. [Osser], and for further results on spheres [Heft], [Oliv]).*

**Proof.** If  $f$  is not surjective, then the degree of  $f$  is zero by Remark 2.5. Thus, we may assume that  $f$  is surjective and we endeavor to construct a homotopy inverse to  $f$ . Set  $\varepsilon = 2 - \text{dil}(f) > 0$  and note that if  $B$  is a ball of radius  $\varepsilon$  in  $S^n$ , then its inverse image  $f^{-1}(B)$  is contained in an open hemisphere. Indeed, let  $y$  be the center of  $B$ , let  $y'$  be the point of  $S^n$  diametrically opposed to  $y$ , and fix an element  $x'$  of  $f^{-1}(y')$ . If  $z \in f^{-1}(B)$ , then

$$d(x', z) \geq \frac{1}{2 - \varepsilon} d(y', f(z)) > \frac{\pi - \varepsilon}{2 - \varepsilon} \geq \pi/2,$$



which shows that  $f^{-1}(B)$  is contained in the open hemisphere opposite  $x'$ .

First suppose  $n = 2$ . By the preceding paragraph, the geodesic simplex formed by three points of  $f^{-1}(B)$  is therefore well-defined. Given a triangulation of  $S^2$ , each of whose simplices are geodesic and contained in a ball of radius  $\varepsilon$ , we associate with each vertex  $v$  a point  $g(v) \in f^{-1}(v)$ . Next, we extend  $g$  to a continuous map  $S^2 \rightarrow S^2$  by requiring that on each triangle with vertices  $v_1, v_2, v_3$ , the extension  $g$  equals the unique linear map whose image is the geodesic simplex having vertices  $g(v_1), g(v_2), g(v_3)$ . To complete the construction, we now show that  $g \circ f$  is homotopic to the identity. Given  $x \in S^2$ , let  $T$  be a triangle containing  $f(x)$  and let  $H$  be an open hemisphere containing  $f^{-1}(T)$ . By definition, each vertex of  $g(T)$  lies in  $f^{-1}(T) \subset H$ , and, since  $g$  is linear and  $H$  is convex,  $g(T) \subset H$  so that  $g \circ f(x) \in H$ . This shows that  $d(x, g \circ f(x)) < \pi$ . Since this inequality holds for each  $x \in S^2$ , a standard argument shows that  $g \circ f$  is homotopic to the identity.

For  $n > 2$ , we proceed similarly, replacing the three points above by  $n + 1$  points and by considering their corresponding spherical  $n$  simplex.

**2.10. Remark:** The hypothesis that  $\text{dil}(f) < 2$  cannot be relaxed to  $\text{dil}(f) \leq 2$  since, for example, there exists a map  $f : S^3 \rightarrow S^3$  having dilatation 2 and degree 4. Indeed, let  $z = (re^{i\theta}, \rho e^{i\varphi})$ , where  $r^2 + \rho^2 = 1$ , and denote a point of  $S^3$ . Define  $f(z) = (re^{2i\theta}, \rho e^{2i\varphi})$ , so that  $f$  is the composition of the maps  $z \mapsto (re^{2i\theta}, \rho e^{i\varphi})$  and  $z \mapsto (re^{i\theta}, \rho e^{2i\varphi})$ , which, as suspensions of the map  $z \mapsto z^2$  of  $S^1 \rightarrow S^1$ , both have degree 2. Thus,  $f$  has degree 4. Moreover, we have  $dz^2 = dr^2 + r^2 d\theta^2 + d\rho^2 + \rho^2 d\varphi^2$ , and  $d(f(z))^2 = dr^2 + 4r^2 d\theta^2 + d\rho^2 + 4\rho^2 d\varphi^2 \leq 4dz^2$ , so that  $\text{dil}_z(f) \leq 2$  for each point  $z$ . Since  $S^3$  is a path metric space, we conclude by Remark 1.8.bis that  $\text{dil}(f) \leq 2$ ; Proposition 2.9 therefore implies that  $\text{dil}(f) = 2$ .

**2.10<sub>2+</sub>** **Remarks and Exercises:** (a) Probably it is not hard to classify maps  $f : S^n \rightarrow S^n$  of maximal possible degree with  $\text{dil}(f) = 2$ , and also with  $\text{dil}(f) = 2 + \varepsilon$ .

(b) Let  $f : \mathbb{R}^{n+1} \rightarrow \mathbb{R}^{n+1}$  be a 1-Lipschitz  $\lambda$ -co-Lipschitz map with  $\lambda < 2$ . Show that  $f$  is one-to-one. Study 1-Lipschitz 2-co-Lipschitz maps  $f : \mathbb{R}^{n+1} \rightarrow \mathbb{R}^{n+1}$  of degree  $\geq 2$ .

In general, a map  $f : S^n \rightarrow S^n$  with a given dilatation cannot have an arbitrary degree.

### 2.11. Proposition:

1. For any  $f : S^n \rightarrow S^n$ , we have  $|\deg(f)| \leq (\text{dil}(f))^n$ .
2. For each  $n$ , there exists a constant  $c_n$  with  $0 < c_n < 1$  and mappings  $f : S^n \rightarrow S^n$  with arbitrarily large degree satisfying the inequality  $|\deg(f)| > c_n(\text{dil}(f))^n$ , i.e.,

$$0 < c_n \leq \limsup_{\deg(f) \rightarrow \infty} \frac{|\deg(f)|}{(\text{dil}(f))^n} \leq 1.$$

**Proof.** We first prove (1) in the case when  $f$  is  $C^1$ . Let  $\omega$  be a normalized volume form on  $S^n$ , i.e.,  $\int_{S^n} \omega = 1$ . By our earlier remarks, we then have  $\deg(f) = \int_{S^n} f^* \omega$  (see [Godb], p. 219), and

$$|\deg(f)| \leq \int_{S^n} \|f^* \omega\| \leq \left( \sup_{x \in S^n} \|Df_x\| \right)^n \int_{S^n} \omega \leq (\text{dil}(f))^n.$$

In the general case, we have that if  $\text{dil}(f) < \infty$ , then there exists for each  $\varepsilon > 0$ , a  $C^1$  map  $f_\varepsilon : S^n \rightarrow S^n$  (obtained from  $f$  by convolution, for example) such that for each  $x \in S^n$ ,  $d(f(x), f_\varepsilon(x)) < \varepsilon$  and  $\text{dil}(f_\varepsilon) \leq \text{dil}(f) + \varepsilon$ . If  $\varepsilon \leq \pi$ , then  $f$  is homotopic to  $f_\varepsilon$ , so that  $\deg(f) = \deg(f_\varepsilon) \leq (\text{dil}(f_\varepsilon))^n \leq (\text{dil}(f) + \varepsilon)^n$ . Since this inequality holds for all  $\varepsilon > 0$ , assertion (1) follows.

(2) We first construct a map  $f_0$  from the  $n$ -ball into  $S^n$  having degree 1 at each point. Fix a point  $p \in S^n$  and let  $B^n(r)$  be the ball of radius  $r$  centered at the origin of the tangent space to  $S^n$  at  $p$ . The mapping  $f_0 : B^n(\pi) \rightarrow S^n$  is then taken to be the restriction of the exponential mapping. By composing with the dilation  $B^n(r) \rightarrow B^n(\pi)$  on the ball of radius  $r$ , we obtain a map  $f_0(r) : B^n(r) \rightarrow S^n$  with dilatation  $\pi/r$ , degree 1 at each point, and which maps  $\partial B^n(r)$  onto  $p'$ , the point of  $S^n$  diametrically opposed to  $p$ .

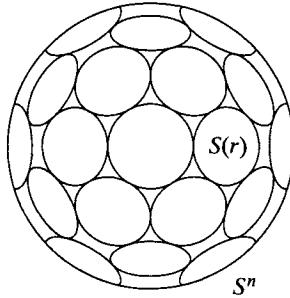
Recall that, even if one cannot pack all of  $S^n$  by small balls of the same radius, there exists a *filling ratio*  $c'_n > 0$ . In other words, if  $S(r)$  is the union of a maximal disjoint collection of radius  $r$  balls having cardinality  $N(r)$ , then

$$\lim_{r \rightarrow 0} \frac{\text{vol}(S(r))}{\text{vol}(S^n)} = c'_n,$$

so that

$$N(r) = \frac{\text{vol}(S(r))}{\text{vol}(B_{S^n}(r))},$$

which is asymptotic to  $c'_n \text{vol}(S^n) / \text{vol}(B^n)r^n$  as  $r \rightarrow 0$ , where  $B^n$  denotes the unit ball in  $\mathbb{R}^n$ .



We define a map  $f_r : S^n \rightarrow S^n$  by first isometrically mapping each small ball of  $S(r)$  onto  $B^n(r)$  and composing with  $f_0(r) : B^n(r) \rightarrow S^n$ , then extending by  $f_r = p'$  on the remainder of  $S^n$ . Then  $\deg(f_r) = N(r)$  tends to infinity as  $r \rightarrow 0$  and  $\text{dil}(f) = \pi/r$ , so that  $\deg(f_r) \sim c_n(\text{dil}(f_r))^n$  with

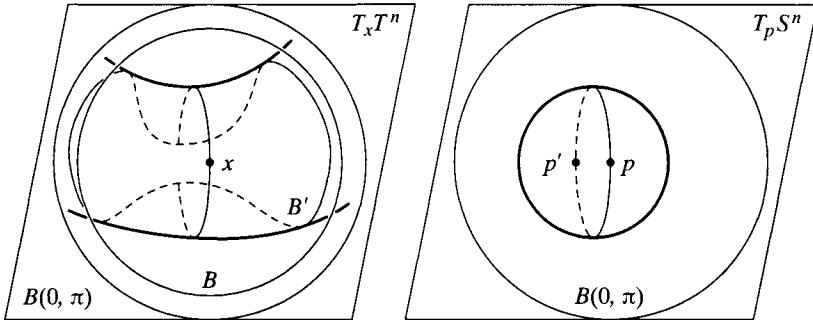
$$c_n = \frac{c'_n \text{vol}(S^n)}{\pi^n \text{vol}(B^n)}.$$

**Remark:** The preceding result is asymptotic, in that it gives a relationship between degree and dilatation when the degree is large, and it will later be improved in Theorem 2.18. The question as to the existence of mappings having a *fixed* degree and small dilatation is no doubt very complicated.

*Maps of flat tori to  $S^n$ .* Let  $T^n$  be a flat torus and let  $\ell$  be the shortest length of a closed curve in  $T^n$  that is not null-homotopic (thus,  $\ell/2$  is the injectivity radius of  $T^n$ ).

**2.12. Proposition:** *There exists a map  $f : T^n \rightarrow (S^n, \text{can})$  with dilatation at most 1 and nonzero degree if and only if  $\ell \geq 2\pi$ .*

**Proof.** For each  $x \in T^n$ , the exponential map defines a diffeomorphism from the ball  $B = B^{T_x T^n}(0, \ell/2)$  onto an open set  $B'$  in  $T^n$  having dilatation 1 (as does its inverse, since the mapping is a local isometry).



We now compose  $\exp^{-1} : B' \rightarrow B$  with a dilation  $B \rightarrow B^{T_x T^n}(0, \pi)$ , the isometry  $B^{T_x T^n}(0, \pi) \rightarrow B^{T_p S^n}(0, \pi)$ , and the exponential map  $\exp : B^{T_p S^n}(0, \pi) \rightarrow S^n$ , for  $p = f(x)$ . The result is a map  $f : B' \rightarrow S^n$  having degree 1 and dilatation  $2\pi/\ell$ , and which satisfies  $\lim_{y \rightarrow \partial B'} f(y) = p'$ . We can extend  $f$  to all of  $T^n$  by setting  $f(T^n \setminus B') = p'$ . Then  $\deg(f) = 1$  and  $\text{dil}(f) = 2\pi/\ell \leq 1$ . If  $\ell \geq 2\pi$ , then  $\text{dil}(f) \leq 1$ , as desired.

Conversely, we now suppose that  $\ell < 2\pi$ . Let  $f : T^n \rightarrow S^n$  be a mapping with dilatation 1; we will show that  $f$  is homotopic to 0. Since  $T^n$  is flat, we may assume that  $T^n = T^{n-1} \times S^1$ , where each  $x \times S^1$  is a curve of length  $\ell < 2\pi$ . Let  $f_0 : T^n \rightarrow S^n$  be the map given by  $f_0(t, s) = f(t, 1)$ . Now, the curve  $S^1 \rightarrow S^n$  defined as  $s \mapsto f(t, s)$  has length  $< 2\pi$ , and  $d(f(t, s), f(t, 1)) < \pi$  for each  $(t, s) \in T^n$  so that  $d(f, f_0) < \pi$ . Thus,  $f$  is homotopic to  $f_0$ , which is not surjective, and so  $f$  has zero degree by Remark 2.5. (Specifically, the homotopy can be constructed explicitly by connecting each pair  $f(x), f_0(x)$  by the unique minimizing geodesic joining them).

**2.12<sub>2+</sub><sup>1</sup> Remark:** The latter argument applies to an arbitrary (say, compact for safety) metric space  $X$  admitting a topological fibration  $p : X \rightarrow B$ , all of whose fibers are circles of length  $< 2\pi$ . Namely, every map  $f : X \rightarrow S^n$  with  $\text{dil}(f) \leq 1$  is homotopic to a map  $f_1$  which factors through another map  $f_0 : B \rightarrow S^n$ , i.e.,  $f_1 = f_0 \circ p$ . Now let us suppose that the fibers  $p^{-1}(b) \subset X$  are  $k$ -dimensional and that their  $k$ -dimensional Hausdorff measures are strictly smaller than that of the unit sphere  $S^k$ . Here, one wants to homotope each map  $f : X \rightarrow S^n$  with  $\text{dil}(f) \leq 1$  to  $f_1$ , sending each fiber  $p^{-1}(b)$  onto a subset of topological (or Hausdorff) dimension  $< k$  in  $S^n$ . Probably one can handle the case in which the fibers are (sufficiently

smooth) surfaces using the argument of §3.6C–C' of [Gro]CC. For  $k \geq 3$ , some results are available for *smooth* fibrations  $p: X \rightarrow B$ . In these cases, our  $f$  can be viewed as a map of  $B$  into the space of  $k$ -cycles in  $S^n$ , namely  $b \mapsto f(p^{-1}(b))$ , which is continuous with respect to the so-called *flat norm*. Then, by Almgren–Morse theory, the map  $B \rightarrow \text{cycles}(S^n)$  is *contractible* for  $\text{mes}_k(f(p^{-1}(b))) < \text{mes}_k(S^k)$ , since every minimal  $k$ -dimensional subvariety in  $S^n$  has  $\text{mes}_k \geq \text{mes}_k(S^k)$ . In particular, if  $\dim(X) = n$ , then  $\deg(f) = 0$ , and so  $f$  is contractible (see Appendix 1 in [Gro]FRM). It is unclear what happens to general smooth maps  $p: X \rightarrow B$  with small  $\text{mes}_k(f(p^{-1}(b)))$  (where the difficulties disappear for sufficiently generic maps  $p$  for which  $p^{-1}(b) \in \text{cycles}(X)$  is continuous in  $b$ ). Finally, one wishes to replace  $S^n$  by a more general Riemannian manifold or metric space  $Y$  and to evaluate the homotopy complexity of maps  $f: X \rightarrow Y$  in terms of  $\sup_{b \in B} \text{mes}_k(f(p^{-1}(b)))$ . An especially interesting  $Y$  in this regard is the unit sphere in  $\ell_\infty^n$ -space, i.e.,  $\mathbb{R}^n$  equipped with the norm

$$\|x\|_{\ell_\infty} = \sup_{1 \leq i \leq n} |x_i|$$

(compare [Gro]FRM).

**2.13. Problem:** What condition on the metric of the torus  $T^n$  guarantees that there exist mappings  $f: T^n \rightarrow S^n$  with degree  $d$  and dilatation 1? We can pose the same question in a slightly different form: Given a metric on  $T^n$ , for which values of  $d$  do there exist mappings  $T^n \rightarrow S^n$  with degree  $d$  and dilatation less than  $D$ ?

## C. Homotopy counting Lipschitz maps

Given two *pointed* metric spaces  $(V, v), (W, w)$ , we denote by  $\#D$  the number of homotopy classes of maps from  $(V, v)$  to  $(W, w)$  that contain at least one map having dilatation  $\leq D$ .

We will use the notation  $[(V, v), (W, w)]$  for the set of equivalence classes of continuous maps from  $V$  to  $W$  under the relation of homotopy relative to  $v$  and  $w$ .

**2.14. Definition:** Let  $X$  be a precompact path metric space. For  $\varepsilon > 0$ , the  $\varepsilon$ -*capacity* of  $X$ , denoted  $\text{Cap}_\varepsilon(X)$ , is the minimum number of radius- $\varepsilon$  balls required to cover  $X$ . In other words,  $\text{Cap}_\varepsilon(X)$  is the minimum number of points in an  $\varepsilon$ -net in  $X$ . (An  $\varepsilon$ -net is a subset  $N$  of  $X$  such that for each  $x \in X$ ,  $d(x, N) < \varepsilon$ .)

This definition enables us to state the following very general theorem.

**2.15. Proposition:** *Let  $(X, x_0), (Y, y_0)$  be precompact, pointed path metric spaces such that  $Y$  has the property that for uniformly “close” mappings from  $X$  to  $Y$  are homotopic (this is the case if  $Y$  is a manifold or a finite polyhedron in the sense of [Span]). Then there exist two constants  $c, c'$  depending only on  $Y$  such that*

$$\#(D) \leq c^{\text{Cap}_1/c'D(X)}.$$

**Proof.** By hypothesis, there exists  $\delta > 0$  independent of  $X$  such that two maps  $f_0, f_1: X \rightarrow Y$  with  $d(f_0(x), f_1(x)) < \delta$  for each  $x \in X$  are necessarily homotopic. Let  $R_Y$  be a  $(\delta/4)$ -net in  $Y$ , set  $\varepsilon = \delta/4D$ , and let  $R_X$  be an  $\varepsilon$ -net in  $X$ . If  $f: X \rightarrow Y$  satisfies  $\text{dil}(f) \leq D$ , then  $f$  maps a ball of radius  $\varepsilon$  in  $X$  into a ball of radius  $\delta/4$  in  $Y$ .

We will first prove that  $\#(D)$  is finite. Suppose that  $f: X \rightarrow Y$  satisfies  $\text{dil}(f) \leq D$  and let  $\hat{f}: R_X \rightarrow \mathcal{P}(R_Y)$  be the mapping defined by  $x \mapsto \{y \in R_Y : d(y, f(x)) < \delta/4\}$ . Suppose that  $g: X \rightarrow Y$  satisfies  $\text{dil}(g) \leq D$  and  $\hat{f}(x) \cap \hat{g}(x) \neq \emptyset$  for each  $x \in X$ . Then for all  $x \in R_X$ , there is some  $y \in R_Y$  such that  $d(y, f(x)) \leq \delta/4$  and  $d(y, g(x)) < \delta/4$ . If  $z \in B_X(x, \varepsilon)$ , then  $d(f(z), f(x)) < \delta/4$ , and  $d(g(z), g(x)) < \delta/4$ , so that  $d(f(z), g(z)) < \delta$ . Since the balls  $B_X(x, \varepsilon)$  for  $x \in R_X$  cover  $X$ , we conclude that  $f$  is homotopic to  $g$ ; in particular, we have just shown that if  $\hat{f} = \hat{g}$ , then  $f$  is homotopic to  $g$ . This proves that  $\#(D) \leq (\text{card } \mathcal{P}(R_Y))^{\text{card}(R_X)}$ .

Next, we choose a representative  $f_\alpha$  for each homotopy class  $\alpha$ , and for each  $x \in R_X$  we fix an element of  $f_\alpha(x)$  denoted by  $\hat{\alpha}(x)$ , so that  $\hat{\alpha}$  is a mapping from  $R_X$  to  $R_Y$ . If  $\hat{\alpha} = \hat{\beta}$ , then  $f_\alpha(x) \cap f_\beta(x) \neq \emptyset$  for all  $x \in R_X$ . Thus,  $f_\alpha$  is homotopic to  $f_\beta$  and so  $\alpha = \beta$ . Thus the map  $\alpha \mapsto \hat{\alpha}$  is injective, and  $\#(D) \leq (\text{card}(R_Y))^{\text{card}(R_X)}$ . By choosing the net  $R_X$  to have the minimum number of points,  $\text{Cap}_\varepsilon(X)$ , we obtain

$$\#(D) \leq c^{\text{Cap}_1/c'D(X)},$$

where  $c = \text{card}(R_Y)$  and  $c' = 4/\delta$ .

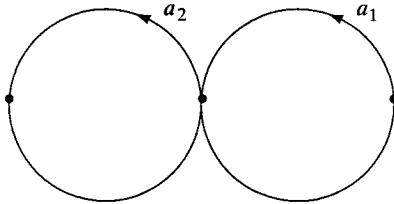
**2.16. Corollary:** *If  $X$  is a compact Riemannian  $n$ -manifold, then Proposition 2.15 implies that  $\#(D) \leq c^{(c'D)^n}$ .*

**Proof.** Here, the question is local, and we know that each point of  $X$  admits a neighborhood that is almost isometric to a Euclidean ball, for which one has the estimate  $\text{Cap}_\varepsilon \simeq C \cdot \varepsilon^{-n}$  as  $\varepsilon \rightarrow 0$ . Indeed, a ball of radius  $\varepsilon$  has volume equal to  $\text{vol}(B(0, 1)) \cdot \varepsilon^n$ ; if  $N$  balls of radius  $\varepsilon$  cover the unit ball, then necessarily  $N \geq \text{vol}(B(0, 1))/\text{vol}(B(0, \varepsilon)) = \varepsilon^{-n}$ . Conversely, it is easy to construct a collection of small balls that cover the unit ball: One

simply takes their centers to be all points whose coordinates are multiples of  $2\varepsilon/\delta n$ , so that the number of balls is on the order of  $\text{vol}(B(0, 1))\varepsilon^{-n}$ .

### 2.17. Examples:

1. If  $X$  is a standard circle and  $Y$  is a bouquet (join) of two standard circles, then  $\#(D) = 4 \cdot 3^{D-1}$ . Indeed,  $[(S^1, p), (S^1 \vee S^1)]$  is the free group on two generators,  $a_1, a_2$ . We obtain a word of length  $k$  in this group by attaching to a word  $x$  of length  $k-1$  one of the letters  $a_1, a_2, a_1^{-1}, a_2^{-1}$  distinct from the last letter of  $x$ . There are three choices at each stage, except for the first, and so there are  $4 \cdot 3^{k-1}$  words of length  $\leq k$ . Thus, the smallest possible dilatation of a map  $X \rightarrow Y$  represented by a word of length  $k$  is exactly  $k$ . Proposition 2.15 gives the bound  $3^{8D}$  since  $\delta = \pi$ ,  $\text{Cap}_\varepsilon(S^1) = 2\pi/\varepsilon$ , and one can take  $R_Y$  to be the net consisting of three points indicated in the figure.



$2_+$ . Let  $X$  be a closed orientable  $n$ -manifold and let  $Y$  be the bouquet of the standard  $n$ -sphere  $S^n$  and the  $k$ -torus  $S^1 \times \cdots \times S^1$  ( $k$  factors). If  $k \geq n$ , then  $\#(D) \geq 2^{c'D^n}$  for some  $c' = c'_n(X) > 0$ . In fact, for each  $D \geq 0$ , there (obviously) exists a map  $\tilde{f}_0 : X \rightarrow \mathbb{R}^k$  serving as the universal covering of the  $k$ -torus, such that  $\text{dil}(\tilde{f}_0) \leq D$  and whose image  $\tilde{f}_0(X) \subset \mathbb{R}^k$  covers at least  $cD^n$  standard unit cubes in  $\mathbb{R}^k$ , each of which is a fundamental domain for the  $\mathbb{Z}^k$ -action on  $\mathbb{R}^k$  giving the  $k$ -torus  $\mathbb{R}^k/\mathbb{Z}^k$ . Since the universal covering  $\tilde{Y}$  of  $Y$  equals  $\mathbb{R}^k$  with  $n$ -spheres attached to the centers of these cubes, one can “bubble”  $\tilde{f}_0$  independently in at least  $cD^n$  points, thus generating  $2^{cD^n}$  mutually nonhomotopic maps  $\tilde{f} : X \rightarrow \tilde{Y}$  of dilatation  $D'$  slightly greater than  $D$ . These project to the required  $2^{c'D^n}$  maps  $f : X \rightarrow Y$  where  $c' = c(D/D')^n$ .

For example, if  $X = S^n$ , then a rough estimate shows that  $c' \geq n^{-10n}$ ; say for  $n = 2$ ,

$$2^{0.0003D^2} \leq \#(D) \leq 4^{\pi^2 D^2}.$$

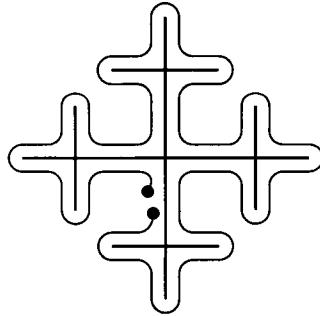
But, if  $k < n$ , then  $\#(D)$  is on the order of  $D^{D^k}$ , namely

$$(c_0 D)^{(c_0 D)^k} \leq \#(D) \leq (c_1 D)^{(c_1 D)^k} \quad (*)$$

for some positive  $c_0, c_1$  depending on  $n$  and  $X$ . Indeed, our map  $\tilde{f}_0: X \rightarrow \mathbb{R}^k$  covers at most  $c'_1 D^k$  cubes, and each bubbling at a given point  $p \in \mathbb{R}^k$  covers the sphere  $S^n$  attached at  $p$  with degree at most  $c_1 D^n$  if we do not allow dilatation  $\geq D$ . This gives the upper bound in (\*), while the lower bound follows by an actual display of independent bubblings at  $\simeq c_0 D^k$  points in  $\mathbb{R}^k$  of degrees  $\leq c_0 D$ .

Notice that the (approximate) upper bound  $\#(D) \lesssim D^{D^k}$  remains valid (and obvious) for any compact manifold  $Y$  whose fundamental group  $\pi_1(Y)$  has polynomial growth of degree  $\leq k$  (see 5.B) and whose universal covering  $\tilde{Y}$  is  $(n-1)$ -connected. (If  $\tilde{Y}$  fails this connectivity requirement, then one can attempt to apply the minimal model argument of 7.B to large balls  $B(D) \subset Y$  and hope for a nontrivial upper bound on  $\#(D)$  if  $\pi_i(Y)$  are finitely generated over  $\pi_1(Y)$ , for instance.)

3+. Let  $Y = S^n \vee S^1 \vee S^1$ , so that  $\tilde{Y}$  equals the regular 3-adic tree Tre with  $S^n$  attached at every vertex. It is not hard to produce maps of the unit  $n$ -ball  $\tilde{f}_D: B^n \rightarrow \text{Tre}$ , with dilatations  $D = 1, 2, \dots$ , such that  $\tilde{f}_D(B) \subset \text{Tre}$  contains at least  $cD^n$  vertices of Tre as shown in the picture for  $n = 1$ .



Bubbling  $\tilde{f}_D$  at these vertices generates  $2^{D^n}$  mutually nonhomotopic maps  $f: X \rightarrow Y$  of dilatation  $\approx D$  for each closed oriented  $n$ -manifold  $X$ .

Another example worth looking at is  $Y = S^n \vee N$ , where  $N$  is a  $k$ -dimensional nilmanifold whose (nilpotent) fundamental group has (polynomial) growth of degree  $m > k$  (i.e., is nonabelian). We want to evaluate the crudest characteristic of  $\#(D)$ , the exponent

$$\delta = \delta(D) = (\log \log \#(D)) / \log(D)$$

as  $D \rightarrow \infty$ . It is clear from the above that  $\limsup_{D \rightarrow \infty} \delta \leq \min(n, m)$ , but we do not know whether this inequality is strict for some  $N$ , or whether  $\delta(D) \rightarrow \min(m, n)$  as  $D \rightarrow \infty$  for all  $N$ . It is clear that  $\delta(D) \rightarrow n$  if

the nilpotent group  $\tilde{N}$  covering  $N$  contains an abelian subgroup  $A$  of rank  $n$ , since the unit ball  $B^n$  can be mapped to  $A \subset \tilde{N}$  with dilatation  $D$  and having image of  $\varepsilon$  capacity  $\simeq D^n$ . On the other hand, such maps  $B^n \rightarrow \tilde{N}$  probably do *not* exist unless the *homogeneous group*  $\tilde{N}_\infty$ , which is the *Hausdorff limit*  $\lim_{\varepsilon \rightarrow 0} \varepsilon \tilde{N}$  (where  $\varepsilon(\tilde{N}, \text{dist}) = (\tilde{N}, \varepsilon \text{ dist})$ , see 3.18 $_{2+}^1$ ) contains an abelian subgroup  $A$  of rank  $n$ .

The following sketchy proof of this fact in a special case emerged in conversations with S. Semmes: Scale  $\tilde{N}$  by  $\varepsilon = D^{-1}$  and pass to a (sub)-limit map  $f_\infty : B^n \rightarrow \tilde{N}_\infty$  as  $D \rightarrow \infty$ . This  $f_\infty$  has dilatation  $\leq 1$  with respect to the limit (as  $D \rightarrow \infty$ ) Carnot–Caratheodory metric  $\text{dist}_\infty$  in  $\tilde{N}_\infty$ . (Recall that  $\tilde{N}_\infty$  admits a dilatation which scales  $\text{dist}_\infty$  by a constant, see [Gro]CC). By the Pansu–Rademacher theorem (see [Pan]CC), this  $f_\infty$  is a.e. differentiable with  $\text{rank}(\mathcal{D}f_\infty) \leq \max \text{rank}(A)$  and so  $\text{mes}_n(f_\infty(B^n)) = 0$  if  $\max \text{rank}(A) < n$ , where  $\max \text{rank}$  is the maximum of the ranks of abelian subgroups  $A \subset \tilde{N}_\infty$ . Unfortunately, it does not imply (at least not in an obvious way) the desired relation

$$\frac{\text{Cap}_\varepsilon(f_D(B^n))}{D^n} \rightarrow 0 \quad (*)$$

for a fixed  $\varepsilon > 0$  and  $D \rightarrow \infty$ . Yet, if  $\tilde{N}_\infty$  is a *nonabelian* group of polynomial growth of degree  $\leq n$ , then the rank inequality  $\text{rank}(\mathcal{D}f_\infty) < n$  does imply  $(*)$  by an argument similar to one used in 2.46.

**Open questions<sub>+</sub>.** (a) Can one obtain a quantitative version of the preceding statement by finding an effective bound on  $\text{Cap}_\varepsilon(f_D(B^n))$ ? For example, does there exist  $\nu > 0$  such that

$$\frac{\text{Cap}_\varepsilon(f_D(B^n))}{D^{n-\nu}} \rightarrow 0$$

as  $D \rightarrow \infty$ . (If so, then a simple counting argument shows that  $\delta(D) < n$  for these  $N$ .)

(b) More generally, let  $Y$  be a compact manifold (or finite polyhedron) with fundamental group  $\Gamma$ . We want to evaluate the  $\varepsilon$ -capacity (or the  $n$ -dimensional measure) of the images of maps  $f_D : B^n \rightarrow \tilde{Y}$  with dilatation  $D$  for  $D \rightarrow \infty$ , where  $\tilde{Y}$  denotes the universal covering of  $Y$ . In particular, we want to decide whether the ratio  $\text{Cap}_\varepsilon(f_D(B^n))/D^n$  necessarily tends to zero as  $D \rightarrow \infty$ .

The same question can be rephrased in terms of a single Lipschitz map  $f : \mathbb{R}^n \rightarrow \tilde{Y}$  and the relation between the volumes of concentric  $R$ -balls in  $\mathbb{R}^n$  and the volumes, or, better, the  $\varepsilon$ -capacities of their images. In particular, we ask whether  $(\text{Cap}_\varepsilon f(B(R)))/R^n \rightarrow 0$  as  $R \rightarrow \infty$ .

Alternatively, a combinatorial version of this question can be described by considering a Lipschitz map  $f: \mathbb{Z}^n \rightarrow \Gamma$ , where both groups are given their respective word metrics (see 3.24<sub>+</sub>), and by then comparing the cardinalities of the balls in  $\mathbb{Z}^n$  to those of their  $f$ -images. Specifically, we want to know when there exists a Lipschitz map  $\mathbb{Z}^n \rightarrow \Gamma$  such that for all balls  $B \subset \mathbb{Z}^n$ ,

$$\text{card}(f(B)) \geq c \cdot \text{card}(B)$$

for some  $c = c(f) > 0$ .

(c) The latter setup can be further generalized by replacing  $\mathbb{Z}^n$  with an arbitrary finitely presented (or just finitely generated) group  $\Gamma_0$  and then studying the rate of decrease of the cardinalities of balls in  $\Gamma_0$  under Lipschitz mappings  $\Gamma_0 \rightarrow \Gamma$ . For example, we want to know if, for given  $\Gamma_0$  and  $\Gamma$ , there exists a Lipschitz map such that all balls  $B \subset \Gamma_0$  (or just the balls  $B$  around a fixed point  $\gamma_0 \in \Gamma_0$ ) satisfy

$$\text{card}(f(B)) \geq \text{const} \cdot \text{card}(B). \quad (*)$$

(Probably the existence of  $f$  satisfying  $(*)$  implies that  $\text{exrank}(\Gamma) \geq \text{exrank}(\Gamma_0)$  by a modification of the corresponding argument for *uniform embeddings* in 7.E2 of [Gro]AI. For example, the product of two free groups  $F_2 \times F_2$  should not admit such a mapping into  $F_2$ .)

(c') Next, we can consider a discrete co-compact (i.e., with compact quotient) isometric action of  $\Gamma_0$  on some metric space  $\tilde{X}$  (playing the role of  $\mathbb{R}^n$  for  $\Gamma_0 = \mathbb{Z}^n$ ) and study Lipschitz maps  $\tilde{X} \rightarrow \tilde{Y}$ . Here, we are again interested in a possible decrease of the  $\varepsilon$ -capacities of balls under such maps.

(c'') Returning to our homotopy counting problem, we can consider concentric balls  $B(R)$  in  $\tilde{X}$  and study homotopy classes of maps  $f_R: B(R) \rightarrow \tilde{Y}$ , where the  $f_R$  are constant on the boundaries  $\partial B(R)$  and have  $\text{dil}(f_R) \leq \text{const}$  for some constant independent of  $R$ . This looks hard in general, and one might simplify the situation by assuming that the  $B(R)$  are homeomorphic to the standard ball  $B^n$  and that  $\tilde{Y}$  is  $(n - 1)$ -connected. (If not, one can count maps  $B(R) \rightarrow \tilde{Y}$  up to *homological* equivalence, which is easier.)

If the group  $\Gamma_0$  above is nilpotent, then the problem can be reduced to the study of Lipschitz maps between *compact* spaces,  $X \rightarrow Y$ , and where  $X$  is now given a Carnot–Caratheodory metric. In fact, much of what we have said in 1<sub>+</sub>–3<sub>+</sub> extends to Carnot–Caratheodory metrics with only minor adjustments (compare [Gro]CC). Here, one may be tempted to allow Carnot–Caratheodory metrics in  $Y$  as well, but this brings in serious local problems (see [Gro]CC).

## D. Dilatation of sphere-valued mappings

The goal of this section is to prove the following theorem:

**2.18. Theorem:** *Let  $V$  be a compact, connected, orientable  $n$ -manifold with (possibly empty) boundary  $\partial V$  and let  $S^n$  be the  $n$ -sphere equipped with an arbitrary Riemannian metric  $g$ . Then the number  $\#(D)$  of homotopy classes of maps  $(V, \partial V) \rightarrow (S^n, s_0)$  of dilatation  $\leq D$  is asymptotic to  $c_g D^n \text{vol}(V)$ , i.e.,*

$$\#(D)D^{-n} \rightarrow c_g \text{vol}(V)$$

as  $D \rightarrow \infty$ , where  $c_g > 0$  is some constant that depends on  $g$  but is independent of  $V$  and the choice of marking  $s_0 \in S^n$ .

**2.19. Definition:** Let  $(X, x_0)$  be a metric space, and let  $B^n$  be the standard unit ball in  $\mathbb{R}^n$ . For  $\alpha \in \pi_n(X, x_0)$ , considered as a homotopy class of mappings  $(B^n, \partial B^n) \rightarrow (X, x_0)$ , we define

$$\|\alpha\| = \left( \inf_{f \in \alpha} \text{dil}(f) \right)^n \text{vol}(B^n).$$

If  $(V, v_0)$  is a pointed, compact Riemannian manifold, we similarly define a function  $[(V, v_0), (X, x_0)] \rightarrow \mathbb{R}_+$  by  $\alpha \mapsto \|\alpha\|$ , where

$$\|\alpha\| = \text{vol}(V) \left( \inf_{f \in \alpha} \text{dil}(f) \right)^n.$$

**2.20. Remark 1:** If  $n = 1$  and  $\alpha \in \pi_1(X, x_0)$ , then  $\|\alpha\|$  is the length of a shortest curve representing  $\alpha$ , so that  $\|\cdot\|$  defines a norm on the group  $\pi_1(X, x_0)$ .

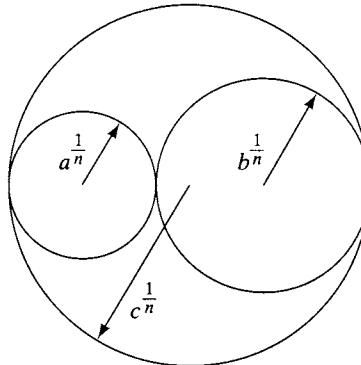
Indeed, by a change of parametrization (i.e., replacing a representative  $f$  of  $\alpha$  by  $f \circ h$ , where  $h$  is a homeomorphism of  $B^1 = [-1, 1]$  isotopic to the identity), we may assume that the local dilatation of  $f$  is constant and equal to  $1/2 \text{length}(f)$ . This reduces the dilatation without changing the homotopy class  $\alpha$  and thus proves the assertion.

The set  $\pi_n(X, x_0)$  has a group structure defined by “juxtaposition” of maps defined on balls that satisfies

**2.21.** For  $\gamma, \delta \in \pi_n(X, x_0)$ ,

$$\|\gamma\delta\|^{1/n} \leq \|\gamma\|^{1/n} + \|\delta\|^{1/n}.$$

Indeed, let  $a, b$  be fixed real numbers with  $a > \|\gamma\|$  and  $b > \|\delta\|$ . Then the classes  $\gamma, \delta$  can be represented by short maps  $f, g$  defined on balls of radius  $a^{1/n}$  and  $b^{1/n}$  whose boundaries are sent to the point  $x_0$ . By placing these balls side-to-side within a ball of radius  $c^{1/n} = a^{1/n} + b^{1/n}$  and extending  $f, g$  to have the constant value  $x_0$  in the large ball, we obtain a short map defined on a ball of radius  $c^{1/n}$  that represents  $\gamma\delta$ . This proves  $\|\gamma\delta\| > c$ .



For  $n = 1$ , we can conclude that  $\|\cdot\|$  is a seminorm on  $\pi_1(X, x_0)$ ; if  $X$  is a locally compact, complete path metric space, then each homotopy class  $\alpha \in \pi_1(X, x_0)$  admits a minimizing loop (Remark 1.12(b)), i.e., a loop whose length equals  $\|\alpha\|$ . It follows that  $\alpha \neq 0$  implies  $\|\alpha\| \neq 0$ , and so  $\|\cdot\|$  is a norm. If  $X$  admits a universal cover  $\tilde{X}$ , then the length structure induced by the projection  $p: \tilde{X} \rightarrow X$  makes  $\tilde{X}$  a locally compact, complete path metric space, and the deck transformations (see [Godb]) of  $\tilde{X}$  are isometries. If  $\tilde{x}_0 \in \tilde{X}$  lies in the fiber over  $x_0$ , then an element  $\alpha \in \pi_1(X, x_0)$  induces an automorphism  $\alpha: \tilde{X} \rightarrow \tilde{X}$  and  $\|\alpha\| = d(\tilde{x}_0, \alpha \cdot \tilde{x}_0)$ . On the other hand, there is no reason for  $\|\cdot\|$  to be a seminorm on  $\pi_n(X, x_0)$  for  $n \geq 2$ .

**Remark 2<sub>+</sub>:** Take the unit sphere  $S^n$  marked at the north pole  $s_+ \in S^n$  and define

$$\|\alpha\|' = (\inf \text{dil}(f'))^n \text{vol}(S^n)$$

where the infimum ranges over all maps  $f': (S^n, s_+) \rightarrow (X, x_0)$  representing  $\alpha$ . Then

$$(\text{vol}(B^n))\|\alpha\|' \leq (\text{vol}(S^n))\|\alpha\| \leq \pi^n (\text{vol}(B^n))\|\alpha\|'.$$

In fact, to bound  $\|\alpha\|$  in terms of  $\|\alpha\|'$ , we first embed  $B^n \subset \mathbb{R}_p^n = T_p S^n$  and then map it to  $S^n$  by  $x \mapsto \exp(\pi x)$ . The dilatation of this map, say  $e: B^n \rightarrow S^n$ , equals  $\pi$ , and so for each  $f': S^n \rightarrow X$ , the composition

$f = f' \circ e: B \rightarrow X$  is homotopic to  $f'$  and satisfies  $\text{dil}(f) \leq \pi \text{dil}(f')$ . Thus,

$$\|\alpha\| \leq \pi^n \|\alpha'\| \frac{\text{vol}(B^n)}{\text{vol}(S^n)}.$$

Conversely, to bound  $\|\alpha\|'$  by  $\|\alpha\|$ , we use the normal projection of the southern hemisphere  $S_-^n \subset \mathbb{R}^{n+1}$  (defined by  $x_{n+1} \leq 0$ ) onto the unit ball  $B^n$  in  $\mathbb{R}^n \subset \mathbb{R}^{n+1}$  (given by  $x_{n+1} = 0$ ). This projection, say  $\varphi: S_-^n \rightarrow B^n$ , satisfies  $\text{dil}(\varphi) \leq 1$ , and so every  $f: (B^n, \partial B^n) \rightarrow (X, x_0)$  gives rise to a map  $f': (S^n, s_+) \rightarrow (X, x_0)$  defined by

$$f'(s) = \begin{cases} x_0 & \text{for } s \in S_+^n \\ (f \circ \varphi)(x) & \text{for } s \in S_-^n \end{cases}$$

and satisfying  $\text{dil}(f') \leq \text{dil}(f)$ . Hence,

$$\|\alpha\|' \leq \frac{\|\alpha\|(\text{vol}(S^n))}{\text{vol}(B^n)}.$$

**2.21<sub>2+</sub>** **Idea of the proof of 2.18.** Define

$$\|\alpha\|^{lim} = \liminf_{p \rightarrow \infty} \frac{\|\alpha^p\|}{p}$$

for all  $\alpha \in \pi_n(X, x_0)$ . If  $X$  is homeomorphic to  $S^n$ , then the group  $\pi_n(X)$  is cyclic, generated by some  $\alpha_0$ , and we claim that the number  $\#(D)$  of homotopically distinct maps  $V \rightarrow X \simeq S^n$  is asymptotic to  $D^n \text{vol}(V)/\|\alpha_0\|^{lim}$ . The proof of this claim divides naturally into two parts:

- (1) Showing that  $\#(D) \succeq D^n \text{vol}(V)/\|\alpha_0\|^{lim}$ , where  $A(D) \succeq B(D)$  stands for  $A(D) \geq (1 - \varepsilon(D))B(D)$  where  $\varepsilon(D) \rightarrow 0$  for  $D \rightarrow \infty$ .
- (2) Establishing the opposite asymptotic inequality,

$$\#(D) \preceq D^n \text{vol}(V)/\|\alpha_0\|^{lim}.$$

To prove (1), we have to generate sufficiently many maps  $V \rightarrow X$  with dilatation  $\leq D$ , starting with a certain collection of mappings  $B^n \rightarrow X$ . This is eventually done by taking, for each  $D > 0$ , a packing of  $V$  by metric balls  $B_j$  such that

- (a)  $\sum_j \text{vol}(B_j) = (1 - \varepsilon) \text{vol}(V)$ , where  $\varepsilon \rightarrow 0$  as  $D \rightarrow \infty$ .
- (b) The radii  $r_j$  of the  $B_j$  satisfy  $r_j \leq \delta$ , where  $\delta \rightarrow 0$  as  $D \rightarrow \infty$ .

- (c) For each value  $r \in \{r_1, \dots, r_j, \dots\}$ , there exist maps of the Euclidean ball  $(B^n, \partial B^n) \rightarrow (S^n, s_0)$  of dilatation  $\leq D/r$  and of degrees  $\pm 1, \pm 2, \dots, \pm p$ , such that

$$(D/r)^n \operatorname{vol}(B) \leq (1 + \varepsilon) p \|\alpha\|^{lim},$$

where  $\varepsilon \rightarrow 0$  as  $D \rightarrow \infty$ . (This implies in particular that the totality of these  $p$  as  $D \rightarrow \infty$  belongs to a subsequence for which  $\|\alpha_0^p\|/p \rightarrow \|\alpha_0\|^{lim}$ .)

Such maps  $B^n \rightarrow S^n$ , composed with the rescaled inverse exponential maps  $B_i(r_i) \rightarrow B^n$ , give us, by a trivial computation, just enough mappings  $V \rightarrow S^n$  constant outside  $B_i(r_i)$  to satisfy (1) (compare with the proof of 2.11 and see the discussion below for a detailed argument).

To prove (2), we must reverse the preceding construction in order to transform maps  $f: V \rightarrow S^n$  of dilatation  $D$  into maps  $(B^n, \partial B^n) \rightarrow (S^n, s_0)$  whose dilatations are suitably controlled by  $D$  and which are of sufficiently high degree. For each  $D$  (where eventually  $D \rightarrow \infty$ ) we again take a packing of  $V$  by  $B_j(r_j)$  satisfying conditions (a) and (b) above and the following:

- (c') The radii  $r_j$  satisfy  $Dr_j \geq \Delta$ , where  $\Delta \rightarrow \infty$  as  $D \rightarrow \infty$ .

Then one can show (see below) that  $f$  can be homotoped to  $f': V \rightarrow S^n$  such that:

(i)  $f'$  maps the union  $\bigcup_j \partial B_j$  to a single point  $s_0 \in S^n$ .

(ii) The dilatation of  $f'$  is only slightly greater than that of  $f$ , i.e.,

$$\operatorname{dil}(f') \leq (1 + \nu)D,$$

where  $\nu \rightarrow 0$  as  $D \rightarrow \infty$ . This  $f'$  gives rise to maps

$$(B^n, \partial B^n) \rightarrow (B_i, \partial B_i) \rightarrow (S^n, s_0),$$

among which one (obviously) finds those for which

$$\frac{\deg(g_i)}{(\operatorname{vol}(B^n)) \operatorname{dil}(g_i)} \geq \frac{\deg(f)}{(\operatorname{vol}(V)) D}.$$

Notice that while the proof of (1) applies to mappings into an arbitrary  $(X, x_0)$  and completely relies on the geometry of the source manifold  $V$  (specifically its property of being locally approximately Euclidean), the proof of (2) makes crucial use of the  $(n-1)$ -connectivity of the target sphere

$S^n$ . This connectivity allows us not only to contract maps  $S^{n-1} \rightarrow S^n$ , but also to do it with negligible increase in dilatation over the course of the contraction.

Now we state the proposition encompassing (1) above.

**2.22+ Packing Proposition:** *For every marked metric space  $(X, x_0)$ , the sequence  $\|\alpha^p\|/p$  always converges to  $\|\alpha\|^{lim}$  for all  $\alpha \in \pi_n(X, x_0)$ . Moreover, if  $V$  is a triangulated  $n$ -dimensional Riemannian manifold of finite total volume, then for every  $\alpha \in \pi_n(X, x_0)$ , there exists a sequence of maps  $f_p: V \rightarrow X$  with the following two properties:*

- (i) *Every  $f_p$  is constant and equals  $x_0 \in X$  on all  $(n-1)$ -simplices of the triangulation of  $V$  as well as on all but finitely many  $n$ -simplices. Furthermore, the map  $f$  represents  $\alpha^p$  in  $\pi_n(X, x_0)$ . This means that the sum of the restrictions of  $f$  to the  $n$ -simplices  $\Delta^n$  (homeomorphic to  $B^n$ ) in  $V$  on which  $f$  is nonconstant, equals  $\alpha^p$  in  $\pi_n(X, x_0)$ .*
- (ii)  $(\text{dil}(f_p))^n/|p| \rightarrow \|\alpha\|^{lim} \text{vol}(V)/\text{vol}(B^n)$  as  $p \rightarrow \infty$ .

Throughout the proof of this proposition, we will use the notation  $B(\omega)$  for the ball of volume  $\omega$  in  $\mathbb{R}^n$ . Any class  $\alpha \in \pi_n(X, x_0)$  defines a homotopy class of mappings  $(B(\omega), \partial B(\omega)) \rightarrow (X, x_0)$  for each  $\omega$ , and

$$\|\alpha\| = \inf \left\{ \omega : \begin{array}{l} \alpha \text{ admits a representative } (B(\omega), \partial B(\omega)) \rightarrow (X, x_0) \\ \text{having dilatation} < 1 \end{array} \right\}.$$

The idea of the proof is now that, given classes  $\alpha_1, \dots, \alpha_k$  having “volumes”  $\|\alpha_1\|, \dots, \|\alpha_k\|$ , we will recover a ball of volume slightly greater than  $\sum_{i=1}^k \|\alpha_i\|$  from the balls of volume  $\|\alpha_i\|$ . By juxtaposing the representatives of the  $\alpha_i$ , we obtain a representative of  $\prod_{i=1}^k \alpha_i$ , and we will then prove that  $\|\prod_{i=1}^k \alpha_i\|$  is close to  $\sum_{i=1}^k \|\alpha_i\|$ .

The first part of the proof describes how to pack a large ball with small balls of a given volume.

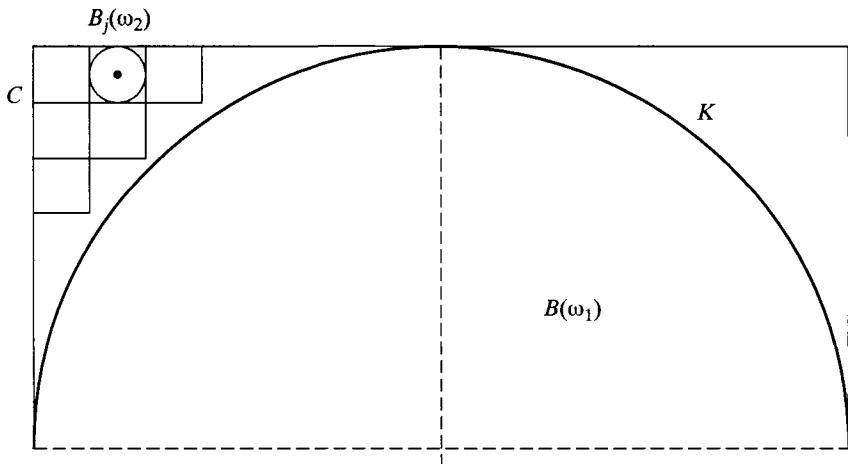
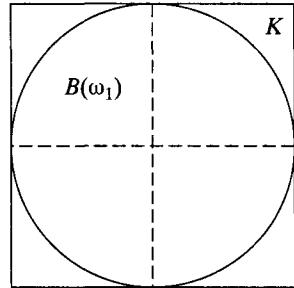
**Lemma:** *Let  $c_n$  be the volume of the unit ball in  $\mathbb{R}^n$  and define  $\lambda = 1 - 2^{-n-1}c_n$ . Let  $\omega_1 \geq \dots \geq \omega_k$  be positive real numbers such that  $\omega_j \geq 100\omega_{j+1}$ . Then there exists a cube  $K \subset \mathbb{R}^n$  and a union  $S$  of disjoint balls in  $K$  having volumes in  $\{\omega_1, \dots, \omega_k\}$  such that  $\text{vol}(K \setminus S) \leq \lambda^k \text{vol}(K)$ .*

**Proof.** Let  $K$  be the  $n$ -cube circumscribed around  $B(\omega_1)$  in  $\mathbb{R}^n$ , so that  $\omega_1 = 2^{-n}c_n \text{vol}(K)$  and

$$\frac{\text{vol}(K \setminus B(\omega_1))}{\text{vol}(K)} = (1 - 2^{-n}c_n) \leq \lambda.$$

Let  $K_2$  be the  $n$ -cube circumscribing  $B(\omega_2)$  in  $\mathbb{R}^n$ . Since  $\text{vol}(K_2)/\text{vol}(K) = \omega_2/\omega_1 \leq 1/100$ , the set  $C$  consisting of the union of the translates of  $K_2$  represented in the figure covers almost all of  $K \setminus B(\omega_1)$  or, more precisely,

$$\text{vol}(C) \geq \frac{1}{2} \text{vol}(K \setminus B(\omega_1)).$$



Next, we place a small ball  $B_j(\omega_2)$  within each small cube so that

$$\text{vol} \left( \bigcup_j B_j(\omega_2) \right) = 2^{-n} c_n \text{vol}(C)$$

whence

$$\text{vol} \left( \bigcup_j B_j(\omega_2) \right) = 2^{-n-1} c_n \text{vol}(K \setminus B(\omega_1)).$$

In other words,

$$\text{vol} \left( K \setminus \left( B(\omega_1) \cup \bigcup_j B_j(\omega_2) \right) \right) \leq \lambda \text{vol}(K \setminus B(\omega_1)) \leq \lambda^2 \text{vol}(K).$$

**2.23. Lemma:** Let  $(\omega_j)_{j \geq 1}$  be a sequence of positive real numbers satisfying  $\omega_j \geq 100\omega_{j-1}$ . For each  $\varepsilon > 0$  and sufficiently large  $\omega$ , there exists within  $B(\omega)$  a union  $S$  of balls whose volumes are among the  $\omega_j$  and

$$\text{vol}(B(\omega) \setminus S) \leq \varepsilon \text{vol}(B(\omega)).$$

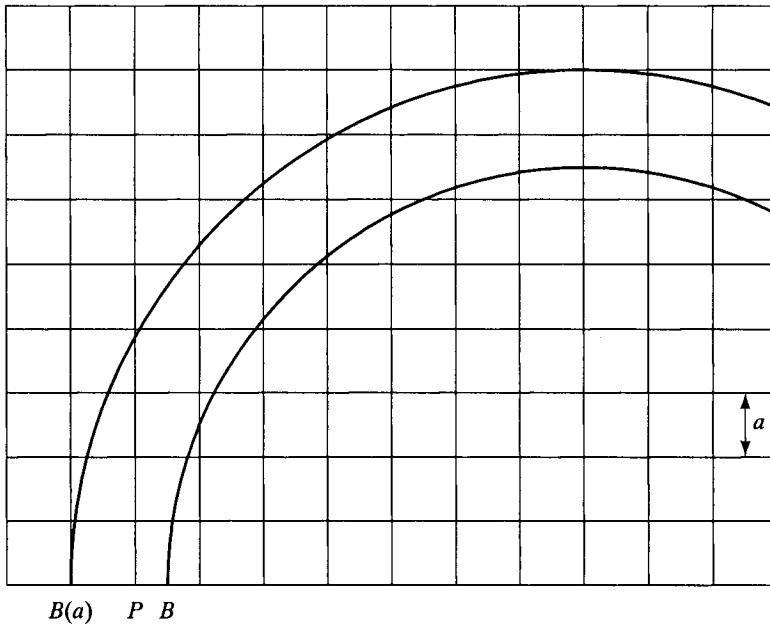
**Proof.** Let  $k$  be an integer such that  $\lambda^k < \varepsilon/2$ . By the preceding lemma, there is a union  $S_K$  of balls within a cube  $K$  of edge  $a$ , all of whose volumes lie among  $\{\omega_k, \dots, \omega_1\}$ , such that  $\text{vol}(K \setminus S) < \varepsilon \text{vol}(K)/2$ . Moreover, if  $R$  is the radius of  $B(\omega)$ , then there exists a union  $P \subset B(\omega)$  of translates of  $K$  that completely covers the ball  $B'$  of radius  $R - a\sqrt{n}$  (see the figure next page).

Thus,

$$\frac{\text{vol}(B(\omega - P))}{\text{vol}(B(\omega))} \leq \frac{\text{vol}(B(\omega) - B')}{\omega} = \frac{R^n - (R - a\sqrt{n})^n}{R^n} \rightarrow 0$$

as  $\omega \rightarrow 0$ . Conversely, there exists  $\omega_0$  such that for  $\omega \geq \omega_0$ , we have  $\text{vol}(B(\omega) \setminus P) < \varepsilon\omega/2$ . If  $S$  is the union of all collections of balls  $S_K = v$  associated with the translates  $K + v$  of  $K$  contained in  $P$ , then  $\text{vol}(P \setminus S) < \varepsilon \text{vol}(P)/2$ , and  $\text{vol}(B(\omega) \setminus S) < \varepsilon\omega$ .

**2.24. Proof of Proposition 2.22+(1).** The proof relies on the following, purely analytic property: If  $(\alpha_p)$  is a sequence of positive numbers satisfying  $\alpha_{i+j} \leq \alpha_i + \alpha_j$  for each  $i, j$ , then the sequence  $\alpha_p/p$  is convergent (for an application of this fact to the spectral radius, see [Dieu], tome 2, Ch. 15, no. 2). When  $n = 1$ , our remarks in 2.21 imply that  $\|\alpha^{p+q}\| \leq \|\alpha^p\| + \|\alpha^q\|$ , and the proof is complete. If  $\liminf_{p \rightarrow \infty} \|\alpha^p\|/p$ , then inequality 2.21 again suffices. Let  $\alpha \in \pi_n(X, x_0)$  and set  $\nu = \liminf_{p \rightarrow \infty} \|\alpha^p\|/p$ . Fix  $\nu' > \nu$ ; we must show that, for sufficiently large  $p$ , we have  $\|\alpha^p\| \leq p\nu'$ . By hypothesis, there exists a sequence  $p_j \rightarrow \infty$  such that  $\liminf_{j \rightarrow \infty} \|\alpha^{p_j}\|/p_j = \nu$ ; we may assume that for each  $j$ ,  $\|\alpha^{p_j}\| < \nu'p_j$ , and so there is a  $\omega_j$  with  $\|\alpha^{p_j}\| \leq \omega_j \leq \nu'p_j$ , and a map  $f_j: (B(\omega_j), \partial B(\omega_j)) \rightarrow (X, x_0)$  representing  $\alpha^{p_j}$  and having dilatation  $\leq 1$ . If the sequence  $(\omega_j)$  is bounded, then we



cannot use Lemma 2.23, but the coarser line of argument in Proposition 2.11 suffices. Indeed, given a mapping  $f_0: (B^n, \partial B^n) \rightarrow (X, x_0)$  representing an element  $\beta$  of  $\pi_n(S^n, p)$ , we can construct a representative  $f_r$  of  $\beta^{N(r)}$  such that  $N(r)(\text{dil}(f_r))^{-n} \geq C(\text{dil}(f_0))^{-n}$ . Since  $N(r)$  can assume any positive integer value, we can generalize Proposition 2.11 as follows: There exists a constant  $C$  depending only on  $n$  such that, for each  $\beta \in \pi_n(X, x_0)$  and  $q \in \mathbb{N}$ , we have  $\|\beta^q\|/q \leq C\|\beta\|$ . On the other hand, given an integer  $p$ , we write  $p = qp_j + r$ , where  $0 \leq r \leq p_j$ , and set  $\beta = \alpha^{p_j}$ . Applying the inequality 2.21 to  $\gamma = \alpha^{qp_j}$  and  $\delta = \alpha^r$ , we obtain

$$\begin{aligned} \left( \frac{\|\alpha^p\|}{p} \right)^{1/n} &\leq \left( \frac{\|\alpha^{qp_j}\|}{p} \right)^{1/n} + \left( \frac{\|\alpha^r\|}{p} \right)^{1/n} \\ &\leq \left( \frac{\|\alpha^{p_j}\|}{p_j + r/q} \right)^{1/n} + \left( \frac{\|\alpha^r\|}{p} \right)^{1/n}. \end{aligned}$$

For each  $\varepsilon > 0$ , there exists a  $j$  such that  $C\|\alpha^{p_j}\|/p_j \leq (\varepsilon/2)^n$ , and so there is a  $p_0$  such that for  $p \geq p_0$  and each  $r$  satisfying  $0 \leq r \leq p_j$ , we have  $\|\alpha^r\|/p \leq (\varepsilon/2)^n$ . Thus, for  $p \geq p_0$ , it follows that  $\|\alpha^p\|/p \leq \varepsilon^n$ , which shows that  $\lim_{p \rightarrow \infty} \|\alpha^p\|/p = 0$ .

If the sequence  $\omega_j$  is not bounded, then by passing to a subsequence, we may assume that  $\omega_j \geq 100\omega_{j-1}$  for each  $j$ . Fix  $\varepsilon > 0$  so that by Lemma 2.23, there exists  $\omega_0$  such that for each  $\omega \geq \omega_0$ , there is a union  $S$  of balls in  $B(\omega)$ ,

each of whose volumes is among the  $\omega_j$ , and  $\text{vol}(B(\omega) \setminus S) \leq \varepsilon\omega$ . Let  $B_k(\omega_j)$  denote such a ball,  $1 \leq k \leq m_j$ . We define a map  $f : (B(\omega), \partial B(\omega)) \rightarrow (X, x_0)$  by setting, for  $1 \leq k \leq m_j$ ,  $f|_{B_k(\omega_j)} = f_j$ , and  $f(B(\omega) \setminus S) = x_0$ . Since  $B(\omega)$  is a path metric space,  $\text{dil}(f) \leq 1$  and  $f$  is a representative of  $\sum_j m_j p_j$ , this proves that  $\|\sum_j m_j p_j\| \leq \omega$ . But  $\text{vol}(S) = \sum_j m_j p_j$  and  $\text{vol}(B(\omega) \setminus S) \leq \varepsilon \text{vol}(B(\omega))$ , so that  $\sum_j m_j \omega_j \geq (1 - \varepsilon)\omega$ . In other words,  $\omega \leq (1 - \varepsilon \sum_j m_j \omega_j)^{-1} \leq \nu'(1 - \varepsilon \sum_j m_j p_j)^{-1}$ , which is the desired inequality for the integer  $p(\omega) = \sum_j m_j p_j$ . When  $\omega$  is a real number larger than  $\omega_0$ , is the integer  $p(\omega)$  greater than  $(\nu'/(1 - \varepsilon))\omega_0$ ? Not quite, since we know only that  $(1 - \varepsilon)\omega/\nu' \leq p(\omega) \leq \omega/\nu$  and  $p(\omega)$  can exceed  $\omega/\nu - (1 - \varepsilon)\omega/\nu' \leq (\nu'/\nu(1 - \varepsilon) - 1)p(\omega)$ . Note that, within the union of balls constructed in Lemma 2.23, the smaller balls comprise a nontrivial space, i.e., for a constant  $\mu > 0$ , we always have  $m_1 \omega_1 \geq \mu \sum_j m_j \omega_j$ , and so  $m_1 p_1 \leq \mu p(\omega)$ . For  $\nu$  sufficiently close to  $\nu'$  and sufficiently small  $\varepsilon$ , we have  $(\nu'/\nu(1 - \varepsilon) - 1) < \mu$ , and the numbers  $p'$  of the form  $km_1 + \sum_j m_j p_j$  for  $0 \leq k \leq m_1$  may eventually exceed  $p(\omega)$ . By forgetting  $m_1 - k$  balls of volume  $\omega_1$  within  $S$ , we construct a short representative of  $\alpha^{p'}$  on the ball  $B(\omega)$ , which proves that, for those of these numbers that exceed  $(\nu'/1 - \varepsilon)\omega_0$ , we have  $\|\alpha^{p'}\| \leq (\nu'/1 - \varepsilon)p'$ . We have therefore proved the first claim of Proposition 2.22 for almost all integers, and we conclude the proof with inequality 2.21.

**2.25. Proof of Proposition 2.22<sub>+</sub> for general  $V$ .** We will need the following version of Lemma 2.23 for each (Riemannian curved) simplex  $\Delta^n$  in the triangulation of  $V$ . We rescale the metric in  $\Delta^n$  so that the resulting simplex  $\Delta^n(\omega)$  has (large) volume  $\omega$ . We then pack almost all of  $\Delta^n(\omega)$  with small, almost Euclidean balls whose volumes lie among the  $\omega_i$  as in 2.24. As before, this gives us the desired short representative of  $\alpha^p$  for  $p = \sum_j m_j \omega_j$  mapping  $(\Delta^n, \partial \Delta^n) \rightarrow (X, x_0)$ . This proves 2.22 for  $V = \Delta^n$ , and the general case follows by choosing an enumeration of the simplices  $\Delta_i^n$  in  $V$  and performing the above constructions for  $\Delta_1^n, \Delta_2^n, \dots, \Delta_d^n$  with  $p_i$  proportional to  $\text{vol}(\Delta_i^n)$ ,  $i = 1, \dots, d$ , while the  $\Delta_{i>d}^n$  go to  $x_0$ . This gives us all we need, since  $p = \sum_{i=1}^d p_i \rightarrow \infty$  and  $d \rightarrow \infty$ .

**Remark<sub>+</sub>:** The preceding argument is quite general in nature and relies exclusively on the following two facts:

- (a) Riemannian manifolds are locally almost Euclidean.
- (b) The Euclidean space  $\mathbb{R}^n$  admits a nontrivial (i.e., having dilatation  $\neq 1$ ) self-similarity.

The latter property is shared by many nilpotent Lie groups  $H$  equipped

with left-invariant Carnot–Caratheodory metrics (such as the Heisenberg group  $\mathbb{H}^{2m+1}$ ), and a general Carnot–Caratheodory manifold  $V$  can be locally approximated by such groups. This suggests the following  $H$ -norm on  $\pi_n(X, x_0)$  for  $n = \dim(H)$ , which is defined using some precompact open topological ball  $B \subset H$ ,

$$\|\alpha\|_B = \left( \inf_{f \in \alpha} \text{dil}(f) \right)^h \text{vol}_h,$$

where  $h$  denotes the Hausdorff dimension of  $H$ ,  $\text{vol}_h$  is the corresponding Hausdorff measure, and the maps  $f$  representing  $\alpha \in \pi_n(X, x_0)$  are those constant at infinity. As before, we set

$$\|\alpha\|_H = \|\alpha\|_B^{lim} = \lim_{p \rightarrow \infty} \frac{\|\alpha^p\|_B}{p},$$

and a straightforward generalization of the argument above shows that the limit exists and does not depend on  $B \subset H$ .

It is also easy to see that  $\|\cdot\|_H$  (as well as our old norm  $\|\cdot\|^{lim} = \|\cdot\|_H$  for  $H = \mathbb{R}^n$ ) is a (possibly degenerate) *norm*, i.e.,

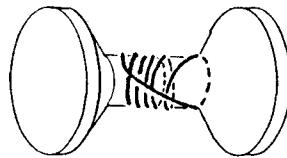
$$\|\alpha\beta\|_H \leq \|\alpha\| + \|\beta\|$$

for all  $\alpha, \beta \in \pi_n(X)$  and  $\|\alpha\|_H \neq 0$ , provided that  $X$  is a compact Riemannian manifold and the rational Hurewicz homomorphism  $\pi_n(X) \rightarrow H_n(X; \mathbb{Q})$  does not vanish on  $\alpha$  (see 1.4.E' in [Gro]CC for the proof and [Gro]DNES for the spectral interpretation of the phenomena described above).

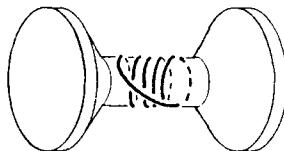
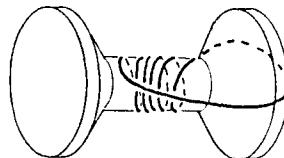
Turning to part (2) of the proof of Theorem 2.18 (sketched in 2.21 $\frac{1}{2}_+$ ), we must show that maps  $V \rightarrow S^n$  which are concentrated on unions of small disjoint balls  $B_j \subset V$  realize (asymptotically) the minimum dilatation in their homotopy class. For this purpose, we need the following fact.

**2.26. Proposition:** *Let  $W$  be a compact,  $(n-1)$ -connected Riemannian  $n$ -manifold and let  $P$  be an  $(n-1)$ -dimensional polyhedron. For each integer  $p$ , there exist numbers  $t_n(p)$  and  $d_0(p)$  such that, for each  $d \geq d_0(p)$  and for each mapping  $f: P \rightarrow W$  of dilatation  $d$ , there is a homotopy between  $f$  and a constant map, defined on  $P \times [0, d^{-1}t_n(p)]$  and having dilatation less than  $(1 + 1/p)d$ .*

It is useful to keep in mind the case when  $n = 2$ : suppose the map  $f$  describes a loop wound around a dumbbell  $W$ , making a sufficiently large number  $d$  of turns around the stem. Each of the  $d$  loops can be removed from the stem if we permit its length to be increased by a number  $K$  depends only on  $W$ .



We cannot release all of the turns simultaneously, since this operation multiplies the dilatation by  $K$ , which is too large. But, if we enlarge the loop by a length equal to  $K$  turns (which only increases the dilatation by a factor of  $1 + K/d$ ), we can remove the loops one by one. The operation is lengthy, having on the order of  $d$  steps. If we permit ourselves a margin of  $(1 + 1/p)$  for the dilatation and if  $d$  is large relative to  $p$ , i.e.,  $d = kpK$ , then we can divide the loop in  $k$  equal parts, on each of which we perform the preceding deformation. This requires a time of  $pK$  and multiplies the dilatation by  $1 + K/Kp = 1 + 1/p$ , neither of which depend on  $d$ .



**2.27. Scolie:** Let  $\Delta$  be a metric space within Lipschitz distance (see Section 3.A)  $L$  from the cube  $[0, \ell]^{n-1}$ . Then there is a constant  $K$  depending only on  $L$  and the  $(n-1)$ -connected manifold  $W$ , such that each mapping  $f: \Delta \rightarrow W$  of dilatation  $\lambda$  contracts to a point via a homotopy  $\Delta \times [0, \lambda^{-1}] \rightarrow W$  of dilatation at most  $K\lambda$ .

**Proof.** Since the question is unaffected by a change of scale, we may assume that  $\lambda = 1$  and replace  $\Delta$  by  $[0, \ell]^{n-1}$ , since the two are connected by a homeomorphism  $\varphi: \Delta \rightarrow [0, \ell]^{n-1}$  for which  $\text{dil}(\varphi)$  and  $\text{dil}(\varphi^{-1})$  are bounded by  $e^L$  (as follows from the definition of  $L$ , see Section 3.A). Then we triangulate  $W$ , denote by  $\delta$  the Lebesgue number of the corresponding covering  $W$  by the stars of the simplices, and use a standard triangulation of

$[0, \ell]^{n-1}$  by simplices of size  $\delta' \simeq \delta$  (which is done by first dividing  $[0, \ell]^{n-1}$  into smaller cubes of the form  $[x, x + \varepsilon]^{n-1}$  for suitable points  $x \in [0, \ell]$  and small  $\varepsilon$ , say  $\varepsilon = \delta/n$ ).

Now  $f: [0, \ell]^{n-1} \rightarrow W$  admits a simplicial approximation  $f_1: [0, \ell]^{n-1} \rightarrow W$  which sends  $[0, \ell]^{n-1}$  to the  $(n-1)$ -skeleton of  $W$  and has  $\text{dil}(f_1) \leq \delta/\delta'$ . Furthermore, if  $\delta$  is small (less than a fraction of the injectivity radius of  $W$ ), then there is a geodesic homotopy  $[0, \ell]^{n-1} \times [0, 1] \rightarrow W$  between  $f$  and  $f_1$  sending each line  $x \times [0, 1]$  to the minimizing geodesic segment between  $f(x)$  and  $f_1(x)$ . This exists since  $\text{dist}(f(x), f_1(x)) \leq \delta$  and the dilatation of this geodesic homotopy is clearly bounded by a constant independent of  $f$ . Finally, we compose this homotopy with a contraction of the  $(n-1)$ -skeleton of  $W$  to a point (recall that  $W$  is  $(n-1)$ -connected) and thus obtain the required contraction of  $f$ .

**2.28.** From now on, we will replace any map  $f: P \rightarrow W$  of dilatation  $d$  by the short map that it defines on the homothetic copy  $dP$  of  $P$ . For an integer  $p$  and real number  $K$  given by Scolie 2.27, we set  $t_n = 3(1 + pK^2 + \dots + p^n K^{2n})$  and let  $i(P)$  be the smallest distance between two disjoint simplices in  $P$  having complementary dimension. We will show by induction that for each  $p$  there exists  $i_n$  such that if  $i(P) \geq i_n$ , then each short map  $f: P \rightarrow W$  admits a homotopy  $H$  to a constant  $w_0$ , defined on  $P \times [0, t_n]$  and having dilatation  $< (1 + 1/p)$ .

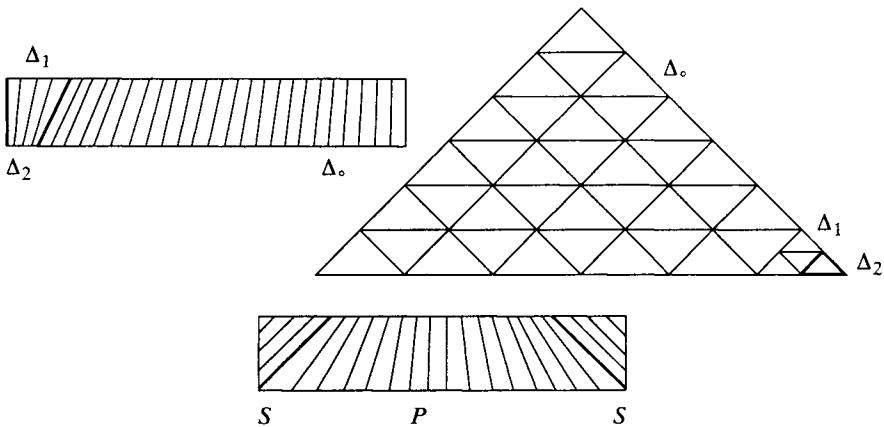
Assuming that this statement is true for  $n-1$ , and given an  $n$  polyhedron  $P$  such that  $i(P) \geq i_{n-1}(pK)^{2n}$ , there exists a subdivision of  $P$  into simplices  $\Delta_0$  such that

$$\text{dist}_L(\Delta, \text{standard simplex dilated by } (pK)^{2n}) \leq L$$

(as in Scolie 2.27). We further subdivide each  $\Delta_0$  into  $2(pK)^n$  simplices  $\Delta_1$ , and each  $\Delta_1$  into  $K^n$  simplices  $\Delta_2$ , in such a way that each  $\Delta_2$  is almost standard, and such that there exists for each inclusion  $\Delta_2 \subset \Delta_1 \subset \Delta_0$  a diffeomorphism  $D_1$  (belonging to a deformation  $D_t$ ,  $0 \leq t \leq 1$ ) with  $D_1(\Delta_1) = \Delta_2$ ,  $\text{dil}(D_1|_{\Delta_1}) \leq 1/K$ , and, for each  $t$ ,  $\text{dil}(D_t) \leq 1 + 1/2p$  (for  $n=1$ , such a deformation is illustrated below).

By the inductive hypothesis, there exists a homotopy of the restriction of  $f$  to the  $(n-1)$ -skeleton (arising from the  $\Delta_2$ -subdivision)  $S$  defined on  $S \times [0, t_{n-1}]$  and having dilatation less than  $1 + 1/4p$ . Since  $i(\Delta_2)$  is very large in comparison with  $t_{n-1}$ , this homotopy can be used to produce an extension of  $f$  to  $P \times [0, t_{n-1}]$  having dilatation again bounded by  $1 + 1/2p$  (see figure).

Now we have  $f(S, t_{n-1}) = w_0$ , and we will describe an extension of  $f$  to



$\Delta_0 \times [0, t_{n-1} + 3]$  such that  $f(\Delta_2, [0, t_{n-1} + 3]) = w_0$  and  $f(x, t_{n-1} + 3) = f(x, t_{n-1})$  if  $x \in \Delta_0 \setminus \Delta_2$ , with dilatation less than  $1 + 1/p$ . In fact, we will accomplish the extension on each simplex simultaneously  $\Delta_0$  (having already chosen the  $\Delta_2$  within each), in such a way as to obtain an extension to  $P \times [0, t_{n-1} + 3]$ .

(1) We perform the deformation  $D_t$ , i.e., we set

$$f(x, t_{n-1} + t) = f(D_t(x), t_{n-1}).$$

By the construction of  $D_t$ , we have

$$\text{dil}(f) \leq 1 + 1/2p + 1/2p \quad \text{and} \quad \text{dil}(f|_{\Delta_2 \times [t_{n-1}+1]}) \leq 1/K.$$

(2) Since  $f(\partial\Delta_2, t_{n-1}) = w_0$ ,  $f(\partial\Delta_1, t_{n-1} + 1) = w_0$ , and since the extension of  $f$  to  $\Delta_1 \times [t_{n-1} + 1, t_{n-1} + 2]$  provided by Scolie 2.27 (with  $\text{dil}(f) \leq K \cdot 1/K = 1$  and  $f(\Delta_1, t_{n-1} + 2) = w_0$ ) is compatible with the trivial extension of  $f$  to  $(\Delta_0 \setminus \Delta_1) \times [t_{n-1} + 1, t_{n-1} + 2]$ , we obtain an extension to all of  $\Delta_0$ .

(3) We perform the inverse of the deformation  $D_t$ , i.e., we set

$$f(x, t_{n-1} + 2 + t) = f(D_{1-t}(x), t_{n-1} + 2),$$

so that  $\text{dil}(f) \leq 1 + 1/K$ ,  $f(\Delta_2, t_{n-1} + 3) = w_0$ , and  $f(x, t_{n-1} + 3) = f(x, t_{n-1})$  for  $x \in \Delta_0 \setminus \Delta_2$ .

To conclude, we perform this operation successively for each  $\Delta_2 \subset \Delta_0$  which gives an extension of  $f$  to the product  $P \times [0, t_{n-1} + 3(p^n K^{2n})]$  such that  $f(P, t_n) = w_0$ .

**2.29. Contracting maps  $V \rightarrow S^n$  on disjoint balls  $B_j$ .** We will apply Proposition 2.26 (or, more precisely, the statement made at the beginning of 2.28) to a sphere  $\partial B^n(R)$  of large radius  $R$  and a short map  $f: B^n(R) \rightarrow S^n$ . We can convert the homotopy defined on  $\partial B^n \times [0, t_{n-1}]$  to an extension of  $f$  to the annulus  $B^n(R + t_{n-1}) \setminus B^n(R)$  with  $f(B^n(R + t_{n-1}))$  equal to the point  $s_0 \in S^n$  and with dilatation less than  $1 + 1/p$ . In the manifold  $V$ , we assume that there is a union  $S$  of small, almost Euclidean balls such that  $\text{vol}(V \setminus S) < \varepsilon \text{vol}(V)$ . Fix a sufficiently large  $\omega$  and a short map  $f: V(\omega) \rightarrow S^n$  that almost minimizes the dilatation in its homotopy class, and set  $k = 1 + 1/p + t_{n-1}(p)/\omega^{1/n}$ . For each ball  $B_j$  of the union  $S$ , we consider  $B_j(\omega)$  as a subset of  $B_j(k\omega) \subset V(k\omega)$ . Then  $f$  is well defined and almost short, and we construct two extensions  $g, h$  of  $f$  to  $V(k\omega)$ .

- (1) There is an extension  $g$  of  $f|_{B_j(\omega)}$  to  $B_j(k\omega)$  of dilatation less than  $k$ , and such that  $g(\partial B_j(k\omega)) = s_0$ . We extend  $g$  to  $V(k\omega)$  by the constant  $s_0$ , so that  $g$  is “concentrated on small balls.”
- (2) We set  $h = f$  on  $V(k\omega) \setminus S(k\omega)$  and also on  $S(\omega)$ , so that it remains to extend  $h$  radially on each annulus  $B_j(k\omega) \setminus B_j(\omega)$ . Since  $h$  is then homotopic to  $f$ , we have  $\deg(h) = \deg(f)$ ; but  $g = h$  on  $S(\omega)$ , whence

$$\begin{aligned} |\deg(f) - \deg(g)| &= (\text{vol}(S^n))^{-1} \int_{V(k\omega) \setminus S(\omega)} (h^* - g^*) \nu_{S^n} \\ &\leq \frac{2k \text{vol}(V(k\omega) \setminus S(\omega))}{\text{vol}(S^n)} \\ &\leq \frac{2k(k-1+\varepsilon)\omega}{\text{vol}(S^n)}, \end{aligned}$$

or, in other words, the ratio  $\deg(f)/\deg(g)$  can be made arbitrarily close to 1 as  $\omega$  tends to  $\infty$ . Since the mapping  $g$  is constructed with the aid of a union of arbitrary balls, we know that  $(\text{dil}(g))^n / \deg(g)$  is close to  $\nu$  when  $\deg(g)$  is large, and this completes part (2) of 2.21 $\frac{1}{2}_+$ .

**2.30. Proof of Theorem 2.18.** Recall that by our preceding definitions,

$$\begin{aligned} \#(D) &= \text{card}\{\text{homotopy classes of maps } V \rightarrow S^n \text{ having a representative} \\ &\quad \text{with dilatation less than } D\} \\ &= \text{card}\{p \in \mathbb{Z} : \exists f: V \rightarrow S^n \text{ with } \deg(f) = p \text{ and } \text{dil}(f) \leq D\} \\ &= \inf_{D' > D} \#\{p \in \mathbb{Z} : \|\alpha_0^p\| \leq \text{vol}(V)D^n\}. \end{aligned}$$

Since  $\|\alpha_0^p\| \sim p\|\alpha_0\|^{lim}$  as  $p \rightarrow \infty$ , it is easy to see that as  $D \rightarrow \infty$ ,

$$\text{card}\{p \in \mathbb{N} : \|\alpha_0^p\| \leq \text{vol}(V)D^n\} \sim \frac{D^n \text{vol}(V)}{\|\alpha_0\|^{lim}}.$$

So that  $\#(D) \sim \text{vol}(V)c_g D^n$  as  $D \rightarrow \infty$ , where  $c_g = 1/\|\alpha_0\|^{lim} + 1/\|\alpha_0^{-1}\|^{lim}$  does not depend on  $V$ .

**2.30<sub>2+</sub>** **Lipschitz extension problem.** Let  $Q$  and  $X$  be metric spaces and let  $P \subset Q$  be a subspace. We then define the *Lipschitz extension function*  $\text{Ex}(\lambda) = \text{Ex}_{P,Q,X}(\lambda)$  as follows: Consider all Lipschitz maps  $f : P \rightarrow X$  which admit continuous extensions to maps  $g : Q \rightarrow X$ , and let  $\text{Ex}(\lambda)$  be the infimum of the numbers  $\Lambda$  such that every  $f$  with  $\text{dil}(f) \leq \lambda$  extends to some  $g$  with  $\text{dil}(g) \leq \Lambda$ . For example, consider  $Q = P \times [0, \ell]$  equipped with the product metric (say with  $\text{dist}_Q = \sqrt{\text{dist}_P^2 + ds^2}$ ), and let  $\text{Ex}_\ell(\lambda)$  be the corresponding extension function from  $P \times 0 \cup P \times \ell$  to  $Q = P \times [0, \ell]$ . Note that  $\text{Ex}_\ell(\lambda)$  is monotone decreasing in  $\ell$  and that the limit  $\text{Ex}_\infty(\lambda)$  measures the infimal  $\Lambda$ , such that every two homotopic maps  $P \rightarrow X$  of dilatation  $\leq \lambda$  can be joined by a homotopy of maps of dilatation  $\leq \Lambda$ . Finally, we can pose the same homotopy question for one of the maps  $P \rightarrow X$  being constant and denote the corresponding *Lipschitz contractibility* function  $\text{Con}(\lambda) = \text{Con}_{P,X}(\lambda)$ .

Proposition 2.26 gives us quite satisfactory information about  $\text{Ex}_\ell(\lambda)$  and  $\text{Con}(\lambda)$  when  $X$  is a compact,  $n$ -connected Riemannian manifold (or a piecewise Riemannian space) and  $P$  is a compact  $n$ -dimensional polyhedron with a piecewise Riemannian metric. Specifically, 2.26 says that  $\text{Con}(\lambda)/\lambda \rightarrow 1$  as  $\lambda \rightarrow \infty$  and, moreover,  $\limsup_{\lambda \rightarrow \infty} \text{Ex}_{\ell/\lambda}(\lambda) = 1 + \varepsilon(\ell)$ , where  $\varepsilon(\ell) \rightarrow 0$  for  $\ell \rightarrow \infty$ . (We suggest that the reader evaluate the actual rate of decay of this  $\varepsilon(\ell)$ .) Thus,  $\text{Ex}_{P,Q,X}(\lambda)/\lambda \rightarrow 1$  as  $\lambda \rightarrow \infty$  for all compact polyhedra  $Q \supset P$ .

## E<sub>+</sub> Degrees of short maps between compact and noncompact manifolds

**2.31. Problem:** What is the value of the constant  $c_g$ ? The expression in 2.30 shows that  $c_g > 0$ , and Proposition 2.11 shows that  $c_g \leq 1$ . In particular, when do we have  $c_g = 1$ ?

**Flat example:** If  $V, W$  are flat tori of the same dimension and volume, there exists a sequences of mappings  $f_k : V \rightarrow W$  such that  $\deg(f_k) \rightarrow \infty$

and  $(\text{dil}(f_k))^n / \deg(f_k) \rightarrow 1$  as  $k \rightarrow \infty$ .

Indeed, we write  $V = \mathbb{R}^n/\Lambda$  and  $W = \mathbb{R}^n/\Lambda'$ , for two lattices  $\Lambda, \Lambda'$  in Euclidean  $n$ -space  $\mathbb{R}^n$ . By hypothesis, these lattices have the same volume, i.e., if  $(e_i)$  and  $(f_i)$  are the bases of  $\Lambda, \Lambda'$ , and if  $L$  is an endomorphism of  $\mathbb{R}^n$  mapping  $e_i$  onto  $f_i$  for each  $i$ , then  $\det(L) = 1$ . Let  $x_{ij}$  denote the  $j$ -th component of  $e_i$  with respect to the basis  $(f_i)$ . From compactness of  $\mathbb{R}^{n^2}/\mathbb{Z}^{n^2}$ , it follows that for each  $\varepsilon > 0$ , there is an integer  $p$  such that for all  $i, j$  we have  $d(px_{ij}, \mathbb{Z}) < \varepsilon$ , or, in other words, if we denote by  $m_{ij}$  the closest integer to  $px_{ij}$  and  $f'_j = \sum_k m_{jk} f_k$ , then  $\|f'_j - p e_j\| < \sqrt{n\varepsilon}$ . From this, we can easily deduce that if  $L'$  is the endomorphism that maps each  $e_i$  to  $f'_i$ , then  $|\text{dil}(1/pL') - 1| < \sqrt{n\varepsilon}$  and  $|(\det(1/pL'))^{1/n} - 1| < \sqrt{n\varepsilon}$ . The endomorphism  $L'$ , which sends  $\Lambda$  onto  $\Lambda'$ , induces a map  $\ell': V \rightarrow W$  whose degree equals the index of the subgroup  $L(\Lambda)$  in  $\Lambda'$ , hence

$$\deg(\ell') = \frac{\text{vol}(L'(\Lambda))}{\text{vol}(\Lambda')} = \frac{\det(L') \text{vol}(\Lambda)}{\text{vol} \Lambda'} = \det(L') \leq p^n (1 + \sqrt{n\varepsilon})^n$$

so that  $\text{dil}(\ell) = \text{dil}(L') \geq p(1 - \sqrt{n\varepsilon})$ . We can therefore make the ratio  $(\text{dil}(\ell))^n / \deg(\ell')$  arbitrarily close to 1.

**2.32. Converse to the flat example and proof of the inequality  $c_g < 1$ .** We want to prove the following statement.

*If closed, connected Riemannian  $n$ -manifolds  $V$  and  $W$  admit a sequence of maps  $f_k: V \rightarrow W$  such that*

$$\text{dil}(f_k) \rightarrow \infty$$

*for  $k \rightarrow \infty$ , and*

$$\limsup_{k \rightarrow \infty} \frac{\deg(f_k)}{(\text{dil}(f_k))^n} \geq \frac{\text{vol}(V)}{\text{vol}(W)}, \quad (*)$$

*then  $V$  and  $W$  are both flat.*

This implies that the constant in Theorem 2.18 satisfies  $c_g < 1$  for  $n \geq 2$ , since no metric  $g$  on  $S^n$  is flat. In fact, we will prove the more general

**2.33. Volume rigidity theorem:** *Let  $V$  and  $W$  be oriented  $n$ -dimensional manifolds, where we assume that  $W$  is compact and connected and that  $V$  satisfies  $\text{vol}(V) < \infty$ . Suppose that there exist maps  $f_k: V \rightarrow W$  with  $\text{dil}(f_k) \rightarrow \infty$  and satisfying*

$$\text{vol}(f_k) \sim (\text{dil } f_k)^n \text{vol}(V) \quad (*)_V$$

*(where  $A(k) \sim B(k)$  signifies  $A(k)/B(k) \rightarrow 1$ ). Then  $V$  and  $W$  are flat, and moreover  $W$  has no boundary.*

**Remark:** This yields the above theorem on degrees, since

$$\deg(f) = \frac{\text{vol}(f)}{\text{vol}(W)},$$

where we recall that

$$\text{vol}(f) \stackrel{\text{def}}{=} \int_V J(f) d\nu_V = \int_V f^*(\nu_W)$$

for the Jacobian  $J(f)$  of  $f$ .

Notice that the Jacobian of  $f$  (or, equivalently, the pullback volume form  $f^*(\nu_W)$ ) is, a priori, defined only for smooth maps  $f$ . The necessary smoothness can always be achieved by a smooth approximation  $f_k$  of given map which represents a negligible perturbation of the dilatations and volumes of these maps. Alternatively, one can appeal to the *Rademacher-Stepanov theorem*, which states that every Lipschitz map is a.e. differentiable and then observe that  $\int_V J(f)$  agrees with the topological degree for Lipschitz maps to the same extent as for smooth ones.

**Proof.** First we observe that the asymptotic relation  $(*)_V$  above is inherited by all open subsets  $U \subset V$ . In fact, if  $U$  is an arbitrary measurable subset in  $V$ , then the relation

$$\int_U J(f_k) d\nu_V \sim (\text{dil } f_k)^n \text{mes}(U) \quad (*)_U$$

follows trivially from the inequality  $J(f_k) \leq (\text{dil } f_k)^n$  and the relation  $(*)_V$  written as

$$\int_U J(f_k) d\nu_V + \int_{V \setminus U} J(f_k) d\nu_V \sim (\text{dil } f_k)^n \text{mes}(U) + (\text{dil } f_k)^n \text{mes}(V \setminus U).$$

This applies in particular to each ball  $B(v, \varepsilon)$  in  $V$  around a fixed point  $v \in V$ . Such balls, when rescaled to unit size become approximately Euclidean. More precisely, the unit Euclidean ball  $B$  admits (rescaled exponential) diffeomorphisms  $e_\varepsilon : B \rightarrow B(v, \varepsilon)$  for all small  $\varepsilon > 0$ , such that  $\text{dil}(e_\varepsilon) \sim \varepsilon$  and  $\text{dil}(e_\varepsilon^{-1}) \sim \varepsilon^{-1}$  for  $\varepsilon \rightarrow 0$ . Such  $e_\varepsilon$  necessarily have  $J(e_\varepsilon) \sim \varepsilon^n$ , and therefore the composed maps  $f_k^0 = f_k \circ e_{\varepsilon_k}$  for  $f_k = f_k|_{B(v, \varepsilon_k)}$  and a suitable sequence  $\varepsilon_k$  (tending to 0 as  $k \rightarrow \infty$ ) satisfy  $(*)_B$ , i.e.,

$$\text{vol}(f_k^0) \sim (\text{dil } f_k^0) \text{vol}(B). \quad (*)_B$$

(In order to satisfy  $(*)_B$ , the sequence  $\varepsilon_k$  must converge to zero quite slowly, say, much slower than  $(\text{dil } f_k)^{-1}$ . In fact, the actual requirement on  $\varepsilon_k$  depends on the rate of convergence of

$$\frac{\text{vol}(f_k)}{(\text{dil } f_k)^n \text{vol}(V)} \rightarrow 1$$

implied by  $(\star)_V$  and the convergences  $\text{dil } e_\varepsilon/\varepsilon \rightarrow 1$  and  $\text{dil } e_\varepsilon^{-1}/\varepsilon^{-1} \rightarrow 1$ .

Thus, we have completed the first step of the proof by showing that *the existence of  $f_k$  with an arbitrary  $V$  implies the existence of a similar sequence for  $V$  equal to the flat Euclidean ball.*

**2.34. Remarks:** (a) A similar reduction  $V \leadsto B$  is possible for maps  $f_k$  satisfying the (nonextremal) relation

$$\text{vol}(f_k) \sim \lambda (\text{dil } f_k)^n \text{vol}(V) \quad (\star)_{V,\lambda}$$

for a given  $\lambda \in [0, 1]$ . Here again one can easily produce a sequence of maps  $f_k^0 : B \rightarrow W$  satisfying  $(\star)_{B,\lambda}$ . But, now one should exercise some care in choosing the centers  $v_k$  of the balls  $B(v_k, \varepsilon_k)$  in  $V$  in order to have the integral

$$\int_{B(v_k, \varepsilon_k)} J(f_k) \nu_V$$

sufficiently large, i.e., on the order of at least  $\lambda \text{vol}(B(v_k, \varepsilon_k))$ .

(b) One could rescale the ball  $B = B(1)$  to  $B(R_k)$  for  $R_k = \text{dil}(f_k^0)$ , thus obtaining *short* maps, say  $f_k^0 : B(R_k) \rightarrow W$  satisfying  $(\star)_{B(R_k),\lambda}$ . Then by a simple compactness argument (left as an exercise for the reader), one can extract a suitable convergent subsequence, thus obtaining a *short map*  $F : \mathbb{R}^n \rightarrow W$ , where  $\mathbb{R}^n$  admits an exhaustion by (nonconcentric!) balls  $B(R_i)$ ,  $i = 1, \dots$  (where these  $R_i$  have nothing to do with the  $R_k$ 's) such that

$$\text{vol}(F|_{B(R_i)}) \sim \lambda R_i^n \text{vol}(B). \quad (\star)_\lambda$$

This can be expressed by saying that *the asymptotic degree* of  $F$  is  $\geq \lambda$ .

Next, in order to prepare the second step of the proof, we observe the following trivial

**2.35. Lemma:** *Let  $J = J(x)$  be a measurable function on the Euclidean ball  $B(R)$  such that  $J \leq 1$  and*

$$\int_{B(R)} J(x) dx \geq (1 - \delta) \text{vol } B(R)$$

*for a given  $\delta \in [0, 1]$ . Then, for every given  $\varepsilon > 0$ , there exists a ball  $B(x, r)$  contained in  $B(R)$ , where  $r \geq \rho(R, \delta, \varepsilon)$  for a fixed function  $\rho$  satisfying  $\rho(R, \delta, \varepsilon) \rightarrow \infty$  as  $R \rightarrow \infty$  and fixed  $\delta \in [0, 1]$ , and such that every  $\varepsilon$ -ball  $B(y, \varepsilon)$  in  $B(x, r)$  satisfies*

$$\int_{B(y, \varepsilon)} J(x) dx \geq (1 - \delta') \text{vol } B(y, \varepsilon),$$

where  $\delta' = \delta'(\delta, \varepsilon) \rightarrow 0$  as  $\delta \rightarrow 0$  and each fixed  $\varepsilon > 0$ .

In other words, the “bad”  $\varepsilon$ -balls which violate the inequality above with  $\delta'$  going to zero much slower than  $\delta$ , cannot intersect every  $r$ -ball in  $B(R)$  with moderately large  $r$ . Otherwise, the assumed lower  $(1 - \delta)$ -bound on the integral  $\int_{B(R)} J$  would be violated, as can be seen from an obvious integration argument.

**2.36. Proposition:** *Given  $f_k: V \rightarrow W$  satisfying the assumptions of the volume rigidity theorem, there exists a short map  $F: \mathbb{R}^n \rightarrow W$  such that*

$$\text{vol}(F|_U) = \text{vol}(U)$$

for every bounded domain  $U \subset \mathbb{R}^n$ .

**Proof.** We used the above map  $f_k^\circ$  of the Euclidean ball  $B$  to  $W$  satisfying  $(\star)_B$  which we transform to short maps  $f_k^\square: B(R_k) \rightarrow W$  for  $R_k = \text{dil } f_k^\circ$ . Then we apply the lemma above to the Jacobian  $J = J_k = J(f_k^\circ)$  for a suitable sequence  $\varepsilon_k$  slowly going to zero as  $k \rightarrow \infty$ . Thus, we obtain balls  $B(x_k, r_k)$  within  $B(R_k)$  with  $r_k \rightarrow \infty$  such that

$$\int_{B(y, \varepsilon)} J(f_k^\square) dx \xrightarrow{k \rightarrow \infty} \text{vol } B(y, \varepsilon)$$

for every fixed  $\varepsilon > 0$  and all  $y \in B(x_k, r_k)$ . Finally, we apply Ascoli’s theorem to the maps  $f_k^\square$  on the balls  $B(x_k, r_k)$ , which can be thought of as the balls in  $\mathbb{R}^n$  around the origin, and obtain as a limit of a convergent subsequence the desired map  $F: \mathbb{R}^n \rightarrow W$ .

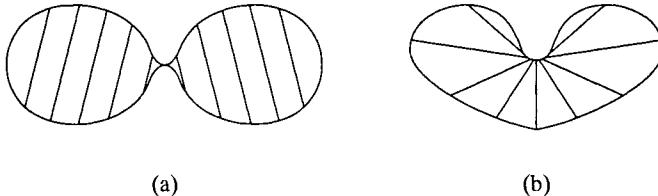
**2.37. Remark:** So far, we have not used the geometry of  $W$ . For example, we could allow up to this point a singular, e.g., piecewise linear (or piecewise smooth) metric. An example of such a metric on  $S^2$  arises as the quotient metric, where  $S^2$  is obtained from the flat torus  $T^2$  via the involution  $t \mapsto -t$ . Here, “ $-$ ” refers to the group structure on  $T^2 = \mathbb{R}^2/\mathbb{Z}^2$ . The quotient map  $f: T^2 \rightarrow S^2$  is obviously short, of degree  $2 = \text{vol}(T^2)/\text{vol}(S^2)$ . This can be composed with self-mappings  $t \mapsto kt$  of the torus, thus producing a sequence of maps  $f_k: T^2 \rightarrow S^2$  with  $\text{dil } f_k = k \rightarrow \infty$  and

$$\text{vol}(f_k) = (\text{dil } f_k)^2 \text{vol}(T^2).$$

This may seem to contradict our theorem, since  $S^2$  is never flat. However, this  $S^2 = T^2/\mathbb{Z}_2$  is nonsmooth, i.e., its metric does not come from a continuous Riemannian metric. In fact, the quotient metric on this  $S^2$  is Riemannian flat apart from 4 singular points where it is isometric to the

Euclidean cone over the circle of circumference  $\pi$  (rather than  $2\pi$ , as is the case at the regular points). This  $\pi$ -angle at the singular points contributes an infinite amount of positive curvature corresponding to the angle deficiency  $\pi = 2\pi - \pi$ . We shall indicate in 2.40 a possible generalization of the volume rigidity theorem to singular spaces.

**2.38. Proving that  $W$  is flat.** Our short map  $F : \mathbb{R}^n \rightarrow W$  is almost everywhere differentiable, and its differential is a.e. isometric. The trouble is that this  $F$  is not *a priori* locally one-to-one (and it should not be, in general, as the remark above shows). The idea is to prove that  $F$  is one-to-one goes as follows. Take a small ball  $B(\varepsilon)$  and suppose that  $F$  is not one-to-one on  $B(\varepsilon)$ . For example,  $F$  might identify two opposite points on the boundary of  $B(\varepsilon)$ , or it might map a boundary point close to the image of the center of  $B(\varepsilon)$ .



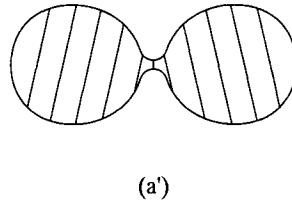
(a)

(b)

Then, we note that  $\text{vol}(F|_{B(\varepsilon)})$  depends only on the map  $F$  on  $S(\varepsilon) = B(\varepsilon)$ , or rather on the resulting hypersurface  $F(S(\varepsilon)) \subset W$  (where we should keep track of multiplicity if  $\partial B(\varepsilon)$  goes through some hypersurface several times, such as the map  $z \mapsto z^2$  on  $S^1 \subset \mathbb{C}$  does). Thus, if we could fill  $F(S(\varepsilon))$  by some ball (or more general  $n$  chain) in  $W$  with volume less than  $\text{vol}(B(\varepsilon))$ , we would arrive at a contradiction, thus showing that  $F$  was indeed 1-1 after all. To this end, we start with the case  $n = 2$  and look at the curve (a) with two opposite points identified. First, we assume that we are in  $\mathbb{R}^2$  and apply the isoperimetric inequality to claim that each half of the curve bounds an area  $\leq B(\varepsilon/2)$  and so the whole curve bounds an area  $\leq \text{Area}(B(\varepsilon))$ . We then recall that a general *riemannian*  $W$  is locally almost Euclidean, and so every sufficiently short curve of length  $\pi\varepsilon$  can be filled by a disk of

$$\text{Area} \leq \pi\varepsilon^2/4 + o(\varepsilon^2),$$

which is smaller than  $\text{Area } B(\varepsilon)/2 = \pi\varepsilon^2/2$  for small  $\varepsilon$ . Since for any pair of collapsing points  $x$  and  $y$  in  $\mathbb{R}^2$  one can find a disk  $B$  in  $\mathbb{R}^2$  having them opposite on  $\partial B$ , we conclude that  $F$  must be *locally one-to-one* in order to have  $\text{vol}(F|_{B(\varepsilon)}) = \text{vol}(B(\varepsilon))$  for small balls  $B(\varepsilon)$ . In fact, this argument also shows that the local inverse map  $F^{-1}$  is Lipschitz, since  $F$  cannot bring two opposite points on  $B(\varepsilon)$  too close together,



since we have a good margin to use in our isoperimetric inequality. Now, once we know that the inverse of  $F$  is Lipschitz, it is necessarily isometric, since its differential is a.e. isometric. (Probably, this extra ‘‘Lipschitz’’ is unnecessary, but we get it for free anyway).

Now we turn to the case  $n \geq 3$  and consider the figure (b) above, where the image  $F(S(\varepsilon)) = \partial B(\varepsilon)$  passes through the image of the center  $F(0) \in W$ . We fill  $F(S(\varepsilon))$  radially from the center  $F(0)$  assuming  $W = \mathbb{R}^n$ . The volume of the resulting conical filling is obviously bounded by

$$\frac{1}{n} \int_{S(\varepsilon)} \|F(0) - F(s)\| ds.$$

Since  $F$  is Lipschitz, the integrand is bounded by  $\varepsilon \text{vol}_{n-1} S(\varepsilon)/n = \text{vol } B(\varepsilon)$ . But, if some point  $F(s_0)$  equals  $F(0)$ , then the integrand becomes smaller than  $\varepsilon/2$  on a definite ball, say of radius  $\varepsilon/2$  in  $S(\varepsilon)$ , which makes the resulting integral smaller than  $\text{vol}(B(\varepsilon))$  by a definite amount  $\geq (2n)^{-n} \varepsilon^n$ . This applies equally to non-Euclidean Riemannian  $W$  for small  $\varepsilon$  and where, furthermore, the condition  $F(s_0) = F(0)$  can be relaxed to  $\text{dist}(F(s_0), F(0)) \leq \lambda \varepsilon$  for a given  $\lambda < 1$ . Thus, one arrives at the conclusion that  $F$  is locally invertible and is moreover a  $\lambda^{-1}$ -Lipschitz map. Then one sees that  $F^{-1}$  is actually an isometry by either letting  $\lambda \rightarrow 1$  or by arguing as before using some  $\lambda > 0$  and appealing to the a.e. isometric property of the differential  $DF$ .

Finally, we observe that a locally isometric map  $\mathbb{R}^n \rightarrow V$  is necessarily a covering map of  $\mathbb{R}^n$  onto (connected)  $V$ , and so  $V$  is flat without boundary.

**2.39. Proving that  $V$  is flat.** We return to the original maps  $f_k : V \rightarrow W$  restricted to a small ball  $B(v, \varepsilon) \subset V$  which we lift to the universal covering,  $B(v, \varepsilon) \rightarrow \tilde{W} = \mathbb{R}^n$  and the scale by  $x \mapsto (\text{dil } f_k)^1 x$  in  $\mathbb{R}^n$ . Thus, we get short maps, say  $\tilde{f}_k : B(v, \varepsilon) \rightarrow \mathbb{R}^n$  satisfying  $\text{vol } \tilde{f}_k \rightarrow \text{vol } B(v, \varepsilon)$ . These subconverge to a short map, say  $\tilde{F} : B(v, \varepsilon) \rightarrow \mathbb{R}^n$  with  $\text{vol } (\tilde{F}) = \text{vol } B(v, \varepsilon)$ , which is necessarily locally isometric by the discussion of the previous section.

**2.40. Remarks and questions.** (a) Let  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  be a short map

satisfying  $\text{vol}(f|_B) \geq \lambda \text{vol}(B)$  for all balls  $B \subset \mathbb{R}^n$ . If  $\lambda > 1 - \varepsilon_n$  for a small positive  $\varepsilon_n$ , then our reasoning in 2.3.8+ shows that  $f$  is one-to-one with  $\varepsilon_2 = 1/2$ , where the latter is sharp, as the map  $z \mapsto z^2/2|z|$  shows. Probably  $\varepsilon_n = 1/2$  works for all  $n \geq 2$  with the extremal example  $(x, z) \mapsto (x, z^2/2|z|)$ .

(b) If  $V$  and  $W$  are singular (riemannian) manifolds, e.g., with bi-Lipschitz Euclidean metrics, then the best one can expect is that  $V$  is locally  $\mathbb{R}^n/G$  for some finite group  $G$ , while  $W$  is locally a ramified covering of  $\mathbb{R}^n$ . For example, if  $n = 2$  and  $W$  is piecewise linear, with angles around vertices  $> \pi$  (nonsingular points have these angles  $> 2\pi$ ), then  $W$  is necessarily flat, since it satisfies a suitable isoperimetric inequality (whose elementary proof is left to the reader). Similarly, if  $V$  is piecewise linear and flat with angles  $< 4\pi$ , then  $W$  is flat. Also, one expects nontrivial topological restrictions on  $V$  and  $W$ . Again, the strongest conclusion would be  $W = \mathbb{R}^n/\Gamma$ , for a discrete group  $\Gamma$  (where the action of  $\Gamma$  on  $\mathbb{R}^n$  may have fixed points) while  $W$  must be some kind of ramified covering of a flat manifold.

(c) In fact, if one is concerned with the topology rather than the geometry of  $V$  and  $W$ , one can consider only Riemannian manifolds and define  $\lambda(d)$  as the minimal possible dilation of maps  $V \rightarrow W$  with  $\text{vol}(f) \geq d$ . (If  $V$  and  $W$  are closed manifolds, then these are the same as maps of degree  $d/\text{vol}(W)$ .) In the above discussion, we were concerned with the extreme case where  $\lambda(d) \sim d^{1/n}$ . This can be relaxed to  $\lambda(d) = O(\alpha d^{1/n})$  for some  $\alpha > 1$  (where  $A(d) = O(B(d))$  means that  $\liminf_{d \rightarrow \infty} A(d)/B(d) \leq 1$ ) and yet it yields strong topological restrictions on  $V$  and  $W$  (compare 2.43+ below). Nevertheless, it is unclear whether  $W$  can be homeomorphic in this case to a connected sum such as  $S^2 \times S^2 \# S^2 \times S^2$  or, more generally, to have hyperbolic rational homotopy type (compare [Grov–Halp]).

If  $V$  is a nonclosed manifold, then, obviously,  $\lambda(d) = O(\alpha d^{1/(n-1)})$  (as is seen with maps sending all of  $V$  to a small ball in  $W$ ), but if  $V$  and  $W$  are both closed, then the mere existence of maps  $f_k : V \rightarrow W$  with  $\deg(f_k) \rightarrow \infty$  imposes non vacuous restrictions on  $V$  and  $W$ . For example,  $W$  does not admit a metric with negative sectional curvature if such  $f_k$  exist for some  $V$  (see Ch. 5.F+). One may expect that in most (?) cases  $\lambda(d) \sim cd^\alpha$  for some constants  $c$  and  $\alpha$ , where  $\alpha = \alpha(V, W)$  appears to be an interesting homotopy invariant of  $V$  and  $W$ .

**Generalizations.** One can allow  $n = \dim(V) < \dim(W)$  and define the volume of a map  $f : V \rightarrow W$  relative to a fixed  $n$ -form  $\omega$  on  $W$  by

$$\text{vol}_\omega f = \int_V f^*(\omega).$$

Then, the topological discussion above makes perfect sense. Furthermore, if  $\text{comass}(\omega) \leq 1$  (compare Ch. 4.D), then the existence of maps  $f_k: V \rightarrow W$  with  $\text{vol}_\omega f_k \sim (\text{dil } f_k)^n$  implies the existence of a path-isometric map  $F: \mathbb{R}^n \rightarrow W$  such that  $F^*(\omega) = \nu_V$ , and if  $W$  is nonsingular (and Riemannian), then this  $F$  is smooth.

Another avenue for generalization is opened by admitting non-Riemannian Carnot–Caratheodory metrics on  $V$ . Here, one can have, for example,  $\lambda d \sim cd^\alpha$  for  $\alpha > \dim V$ . In fact, the maximal possible  $\alpha$  here equals the *Hausdorff dimension* of  $V$  (see 2.47 and [Gro]CC).

**2.41. Asymptotic degree and elliptic manifolds.** Consider equidimensional Riemannian manifolds  $V$  and  $W$ , where  $V$  is assumed to be connected and oriented, take a Lipschitz map  $f: V \rightarrow W$ , and let

$$\delta(U) = \text{vol}(f|_U)/\text{vol}(U)$$

for all bounded (i.e., precompact) domains  $U \subset V$ . Here, we are interested in the case of  $\text{vol}(V) = \infty$ , e.g.,  $V = \mathbb{R}^n$ , and we study the asymptotics of  $\delta(U)$  for domains  $U$  exhausting  $V$ . The simplest exhaustion is that given by concentric balls  $B(R) = V$  for  $R \rightarrow \infty$ , but we can also use exhaustions by nonconcentric balls.

**Example:** Suppose  $V = \mathbb{R}^n$  is exhausted by (possibly nonconcentric) balls  $B(R)$  such that  $\delta(B(R)) \rightarrow (\text{dil}(f))^n$ . Then the volume rigidity theorem applies to the maps  $f|_{B(R)}$  (where, strictly speaking, the balls  $B(R)$  should all be scaled to unit size) and shows that  $W$  is flat, provided that it is a *complete riemannian* manifold.

Now, we shift into the topological gear and ask ourselves when a given Riemannian manifold  $W$  admits a short (or just Lipschitz) map  $f: \mathbb{R}^n \rightarrow W$  with *nonzero asymptotic degree*, i.e., having  $\limsup_{R \rightarrow \infty} \delta(B(R)) > 0$  for some exhaustion of  $\mathbb{R}^n$  by balls. Such manifolds are called *elliptic*. Obviously, this property is a homotopy invariant of  $W$  when  $W$  is a *closed* manifold. One expects such closed elliptic  $W$  to have *elliptic* (i.e., nonhyperbolic, see [Grov–Halp]), *rational homotopy type*. But, we do not even know whether  $S^2 \times S^2 \# S^2 \times S^2 \rightarrow$  is elliptic. On the other hand, if  $W$  is elliptic, then its fundamental group must be rather small.

**2.42. Theorem:** *If  $W$  is elliptic, then the balls  $\tilde{B}(R)$  in the universal cover  $\tilde{W}$  satisfy*

$$\limsup_{R \rightarrow \infty} \frac{\text{vol } \tilde{B}(R)}{R^n} < \infty \tag{*}$$

**Proof.** Lift  $f$  to a map  $\tilde{f}: \mathbb{R}^n \rightarrow \tilde{W}$  and observe that this does not change the normalized volume of  $f$ , namely

$$\delta_f(U) = \delta_{\tilde{f}}(U)$$

for all  $U \subset V$ . On the other hand, if  $\pi_1(W)$  is infinite, then  $\text{vol}_{\tilde{f}}(U)$  depends only on  $\tilde{f}|_{\partial U}$ . In particular, if  $\tilde{f}(\partial U) \subset W$  bounds an  $n$ -chain (i.e., a multi-domain in  $W$ ) of volume  $A$ , then

$$\text{vol}(f|_U) = \text{vol}(\tilde{f}|_U) \leq A.$$

We apply this to  $U = B(R)$  for  $R \rightarrow \infty$  and observe that  $\text{vol}_{n-1} \tilde{f}(\partial B(R)) = O(R^{n-1})$  since  $\tilde{f}$  is short. Now, if it were true that  $\limsup \text{vol}(\tilde{B}(R))/R^n = \infty$ , then we could fill the hypersurface  $\tilde{f}(\partial B(R))$  in  $\tilde{W}$  by a chain of volume  $\varepsilon(R)R^n$ , with  $\varepsilon(R) \rightarrow 0$  for  $R \rightarrow \infty$  according to a theorem by Varopoulos (see Ch. 6.E).

**2.43. Corollary:** *If  $W$  is elliptic and its universal covering is contractible, then the fundamental group  $\pi_1(W)$  is virtually abelian, i.e., it contains an abelian subgroup of finite index.*

**Proof.** The relation (\*) says that  $\tilde{W}$ , and hence the fundamental group  $\pi_1(W)$  has polynomial growth of degree  $n$ , and so  $\pi_1(W)$  is virtually nilpotent (see 5.7+–5.10). But, it was observed a long time ago by Bass (see [Bass]) that if a torsion free nilpotent group  $\Gamma$  has its degree of growth less than or equal to its homological dimension, then  $\Gamma$  is abelian. Since our  $\Gamma \subset \pi_1(W)$  appears as the fundamental group of a closed, aspherical  $n$ -manifold (a finite covering of  $W$ ), it has homological dimension  $n$ , and Bass' observation applies.

**2.44. Question:** *Is the assumption of asphericity of  $W$  (i.e., of the contractibility of  $\tilde{W}$ ) truly needed to conclude that  $\pi_1(W)$  is virtually abelian?*

What is immediately clear at this stage is that  $\pi_1(W)$  is virtually nilpotent of growth degree  $\leq n$ . This does not exclude, for example,  $W = S^2 \times N/\Gamma$ , where  $N$  is the 3-dimensional Heisenberg group and  $\Gamma$  is a lattice in  $N$ . One knows that every large domain  $\Omega \subset \tilde{W}$  for this  $W$  satisfies the *Pansu isoperimetric inequality*

$$\text{vol}_5(\Omega) \leq \text{const}(\text{vol}_4(\partial\Omega))^{4/3}$$

(compare Ch. 6.E<sub>+</sub>). In our case, the boundary  $\partial\Omega$  comes by a short map from the Euclidean 4-sphere  $S(R)$ , and thus we have  $\text{vol}_4(\partial\Omega) = O(R^4)$ .

What we need in order to prove that this  $W$  is nonelliptic is the asymptotic relation

$$\text{vol}_5(\Omega) = o(R^5)$$

for  $R \rightarrow \infty$ , rather than  $O(R^{16/3})$  by somehow using the special geometry of  $\partial\Omega$ . (Notice that  $\Omega$  in this case is a multiple domain, but this may only improve the isoperimetric inequality.) Some nontrivial information concerning the shape of  $\partial\Omega = f(S(R))$  for  $R \rightarrow \infty$  can be obtained by rescaling  $\tilde{W}$  by  $\varepsilon = R^{-1}$  and passing to the limit as  $\varepsilon \rightarrow 0$  (see 3.18 $\frac{1}{2}+$ ), where the (Carnot–Caratheodory) geometry of the limit space  $\lim_{\varepsilon \rightarrow 0} \varepsilon \tilde{W}$  severely restricts the size of  $f(S(R)) \subset \tilde{W}$  (as well as that of  $f(B(R))$ ) for large  $R$  (compare 3 $_+$  in 2.17). This allows us, for example, to rule out nonabelian nilpotent groups of growth exactly  $n$ . Namely, if the fundamental group  $\pi_1(W)$  is *not* virtually abelian, then the relation  $(*)$  in 2.42 can be improved as follows:

$$\limsup_{R \rightarrow \infty} \frac{\text{vol}(\tilde{B}(R))}{R^{n-1}} < \infty. \quad (**)$$

**Sketch of the proof.** By rescaling our maps by  $\varepsilon = R^{-1}$ , we get maps  $f_\varepsilon: B(1) \rightarrow \varepsilon \tilde{W}$  which subconverge as  $\varepsilon \rightarrow 0$  to a Lipschitz map  $f_0: B(1) \rightarrow N$ , where  $N$  is the Hausdorff limit of  $\varepsilon \tilde{W}$  as  $\varepsilon \rightarrow 0$  (compare 3 $_+$  in 2.17), which is in our case a nonabelian nilpotent Lie group with a (non-Riemannian!) Carnot–Caratheodory metric. Hence, by the Pansu–Rademacher theorem,  $f_0$  is a.e. differentiable, and  $\text{rank } Df_0 \leq n - 1$  a.e. Now assume that  $(**)$  fails to be true, which yields that the volume growth is exactly of degree  $n$  for  $\pi_1(W)$  and  $\tilde{W}$ . Then, the inequality  $\text{rank } Df_0 \leq n - 1$  a.e. for the limit map  $f_0$  implies that the image of  $B(R)$  under  $f$  satisfies

$$\frac{\text{vol}(f(B(R)))}{R^n} \rightarrow 0$$

as  $R \rightarrow \infty$ . A priori, this does not rule out the possibility of  $\text{vol}(f|_{B(R)}) \sim R^n$ , since the latter volume is counted with multiplicity. Nevertheless, the presence of high multiplicity enhances the power of the (Varopoulos) isoperimetric inequality in  $\tilde{W}$ , which reads in our case (compare Ch. 6.E $_+$ )

$$\text{vol}(\Omega) \leq \text{const}(\text{vol}_{n-1}(\partial\Omega))^{n/(n-1)}. \quad (\star)$$

But, if  $\Omega$  is a multiple domain given by a map  $I: \Omega \rightarrow \tilde{W}$  (which can be assumed to be an immersion), and  $\mu(w) = \text{card}(I^{-1}(w))$  is the multiplicity of  $\Omega$  at the points  $w \in \Omega_1 = \text{im}_I(\Omega)$ , then the oriented volume

$$\text{vol}(\Omega) \stackrel{\text{def}}{=} \int_{\Omega} I^*(d\nu_{\tilde{W}})$$

can be bounded in terms of the average multiplicity  $\bar{\mu} = (\int_{\Omega} \mu \, d\nu_{\tilde{W}}) / \text{vol}(\Omega_1)$  by

$$\text{vol}(\Omega) \leq \text{const } \mu^{-1/(n-1)} (\text{vol}(\partial\Omega))^{n/(n-1)}, \quad (\star\star)$$

as follows from  $(\star)$  applied to the subdomains  $\Omega_i \subset \Omega_1$ , where  $\mu \geq i$ , for  $i = 1, 2, \dots$ . This applies to  $\partial\Omega = f(\partial B(R))$  (although  $f$  does not have to be an immersion on  $B(R)$ ), and shows that  $\text{vol}(f|_{B(R)})/R^n \rightarrow 0$ , thus proving our assertion by contradiction.

**Example:** The manifold  $S^2 \times N/\Gamma \times N/\Gamma$ , where  $N$  is the Heisenberg group, is nonelliptic.

#### 2.45. Elliptic manifolds $W$ with $\pi_1(W) = \mathbb{Z}^n$ for $n = \dim(W)$ .

**Theorem:** If  $\pi_1(W) = \mathbb{Z}^n$  and the universal covering  $\tilde{W}$  admits a sequence of short maps  $f_i$  from the Euclidean balls  $f_i : B(R_i) \rightarrow \tilde{W}$  such that  $\text{vol } f_i \geq \text{const } R_i^n$  for some const > 0 and  $R_i \rightarrow \infty$ , then  $\tilde{W}$  is contractible.

**Proof.** Take a smooth map  $\alpha : W \rightarrow T^n$  which induces an isomorphism on  $\pi_1$ , and look at the corresponding maps  $\tilde{\alpha} : \tilde{W} \rightarrow \mathbb{R}^n = \tilde{T}^n$ .

**2.46. Lemma:** Let  $f_i : B(R_i) \rightarrow \tilde{W}$  be short maps such that  $\text{vol}(f_i) \geq \text{const } R_i^n$  for  $R_i \rightarrow \infty$ . Then there exist (Euclidean) balls  $B(r_i) = B(x_i, r_i) = B(R_i)$  with  $r_i \rightarrow \infty$  such that the image of the sphere  $S(r_i)$  under the composition  $\alpha \circ f_i$  does not intersect the ball

$$B(y_i, cr_i) \subset \mathbb{R}^n \quad \text{for} \quad y_i = \alpha \circ f_i(x_i)$$

and a fixed  $c > 0$  (independent of  $i$ ) and such that the normal projection  $P$  to the boundary  $\partial B(y_i, cr_i)$  gives us a map of degree 1 or  $-1$  from the sphere  $S(r_i)$  to  $S(\rho) = \partial B(y_i, cr_i)$ , i.e., the composition  $P \circ \alpha \circ f_i : S(r) \rightarrow S(\rho)$  has  $|\deg| = 1$ .

**Proof.** We rescale the maps  $f_i$  by  $\varepsilon_i = R_i^{-1}$  as before, obtaining a sublimit map  $f_\infty : B(1) \rightarrow \mathbb{R}^n = \lim_{\varepsilon_i \rightarrow 0} \varepsilon_i \tilde{W}$ . This composes with the rescaled linear map  $\tilde{\alpha}$ , say  $\tilde{\alpha}_0 : \mathbb{R}^n = \lim_{\varepsilon_i \rightarrow 0} \varepsilon_i \tilde{W} \rightarrow \mathbb{R}^n = \lim_{\varepsilon_i \rightarrow 0} \varepsilon_i \mathbb{R}^n$ , where the resulting composition  $\tilde{\alpha}_0 \circ f_\infty$  could have been obtained without any Hausdorff limits by just composing the maps

$$B(1) \xrightarrow{R} B(R) \xrightarrow{\tilde{\alpha} \circ f} \mathbb{R}^n \xrightarrow{\varepsilon} \mathbb{R}^n,$$

(where  $R$  stands for the map  $x \mapsto Rx$  and  $\varepsilon$  stands for  $y \mapsto \varepsilon y$  with  $\varepsilon = R^{-1}$ ) and passing to the sublimit as  $R = R_i \rightarrow \infty$ .

The limit map  $\tilde{\alpha}_0 \circ f_\infty$  is a.e. differentiable by the Rademacher theorem, and  $\text{rank}(\tilde{\alpha}_0 \circ f_\infty(x_0)) = n$  at some point of differentiability in the interior of  $B(1)$ , since otherwise  $\text{rank} \leq n - 1$  would enhance the (Euclidean) isoperimetric inequality for multiple domains bounded by  $f_i(S(R_i)) \subset \tilde{W}$  and would imply  $\text{vol}(f_i|_{B(R_i)}) = o(R_i^n)$  as before. Now, since  $f_0$  has a nonsingular differential at  $x_0$ , it is approximately nonsingular linear on a small ball  $B(x_0, \delta)$  in  $B(1)$ , and so the approximating maps  $\tilde{\alpha} \circ f_i$  are approximately non singular linear on the corresponding balls  $B(x_i, r_i = \delta R_i) \subset B(R_i)$ .

Now, in order to show that  $W$  is a homotopy torus, we will prove that  $H_i(\tilde{W}) = 0$  for  $i > 0$ . In fact, suppose that there is a nontrivial cycle  $\mathcal{C}$  in  $\tilde{W}$ , and take an infinite cycle  $\mathcal{C}'$  of complimentary dimension having nonzero intersection index with  $\mathcal{C}$ . One can assume that  $\mathcal{C}$  is located near the point  $f_i(x_i) \in \tilde{W}$  for large  $i$ , so that the boundary of  $B(x_i, r_i)$  is sent by  $f_i$  far from  $\mathcal{C}$ , and the maps  $f_i|_{B(r_i)}$  has  $|\deg| = 1$  over  $\mathcal{C}$ . Thus,

$$f_i^{-1}(\mathcal{C}) \cap f_i^{-1}(\mathcal{C}') = \pm \mathcal{C} \cap \mathcal{C}' \neq 0,$$

where  $f_i^{-1}$  refers to  $f_i = f_i|_{B(r_i)}$ , which is impossible (since  $H_*(\mathbb{R}^n) = 0$ ), and so  $\mathcal{C} \cap \mathcal{C}' = 0$  after all. Consequently, every cycle  $\mathcal{C}$  in  $\tilde{W}$  of positive dimension is homologous to zero.

**Example:** The connected sum  $T^4 \# S^2 \times S^2$  is non elliptic.

**Question:** Does every elliptic  $W$  admit a nonconstant quasiregular map  $f_0 : \mathbb{R}^n \rightarrow W$ ? It would be interesting to prove this by finding some extremal map  $f : \mathbb{R}^n \rightarrow W$  with maximal possible volumes  $\text{vol}(f|_{B(R)})$  for  $R \rightarrow \infty$  and then showing that such an extremal map is quasiregular. (Such a proof could go beyond mere topology and apply to some open Riemannian manifolds  $W$ ). Conversely, the Bloch–Brody principle suggests that the existence of  $f_0$  makes  $W$  elliptic (compare 6.43 $\frac{2}{3}$  $_+$ ).

**Exercise:** Show that the torus  $T^n$  minus a point equipped with the metric induced from  $T^n$  is nonelliptic. *Hint:* Study the isoperimetry of Euclidean spheres  $S^{n-1}(R)$  mapped by Lipschitz maps to  $\mathbb{R}^n$  minus a  $\delta$ -dense subset, where  $R \rightarrow \infty$  while  $\delta$  is held constant.

**Question:** Is the sphere  $S^n$  minus an infinite subset ever elliptic? (The negative answer is suggested by a theorem of Rickman, which claims that every quasiregular map  $\mathbb{R}^n \rightarrow S^n$  can omit only finitely many points.)

**2.47. Non-Euclidean generalizations.** Let us generalize the discussion above by looking at volume efficient ways of Lipschitz-wrapping up  $W$  in

non-Euclidean paper. Namely, we take some (complete, open) manifold  $V$  and study  $\lambda$ -Lipschitz maps  $f: V \rightarrow W$  satisfying  $\text{vol}(f|_{\Omega_i}) \sim \mu \text{vol}(\Omega_i)$  for some exhaustion of  $V$  by suitable bounded domains  $\Omega_i$ , for  $i = 1, 2, \dots$ , where we wish  $\mu = \mu(\lambda)$  to be relatively large, in particular  $> 0$ . If  $V = \mathbb{R}^n$ , then  $\mu(\lambda) = \lambda^n \mu(1)$ , but for general  $V$ , one may necessarily have  $\mu(\lambda)/\lambda^n \rightarrow 0$  for  $\lambda \rightarrow 0$ , even for such simple manifolds  $W$  as the sphere  $S^n$ . On the other hand, for a fixed  $\lambda$ , say  $\lambda = 1$ , the Euclidean theory extends with minor adjustments to several classes of  $V$ . For example, if  $V$  is a nilpotent Lie group with a left-invariant Riemannian metric, then  $V$ -ellipticity of  $W$  implies that  $\Gamma = \pi_1(W)$  is virtually nilpotent of growth  $\Gamma \leq \text{growth } V$ . Furthermore, if  $V$  and  $\pi_1(W)$  have equal growth, then the limit spaces  $\lim_{\varepsilon \rightarrow 0} \varepsilon V$  and  $\lim_{\varepsilon \rightarrow 0} \varepsilon \Gamma$  are bi-Lipschitz equivalent (which implies that the graded Lie algebras associated to  $V$  and  $\Gamma$  are isomorphic) and the universal covering  $\tilde{W}$  of  $W$  is contractible.

The proofs of the results above can be easily derived along the Euclidean guidelines with the use of the Varopoulos isoperimetric inequality in nilpotent groups (see Ch. 6.E<sub>+</sub>). We suggest that the reader look into this.

The “rigid” example 2.41<sub>2+</sub> generalizes to those (not only nilpotent)  $V$  which admit an isometry group  $\Gamma$  with  $V/\Gamma$  compact and where the exhaustion  $\Omega_i$  in question satisfies  $\text{vol}(\Omega_i)/\text{vol}_{n-1}(\partial\Omega_i) \rightarrow \infty$  for  $i \rightarrow \infty$ . Here, an easy argument shows that the existence of a short map  $f: V \rightarrow W$  with  $\text{vol}(f|_{\Omega_i}) \sim \text{vol}(\Omega_i)$  implies that there exists a locally isometric (and hence, covering) map  $V \rightarrow W$ .

The volume rigidity theorem also generalizes, at least to the nilpotent framework, as long as one passes to Carnot–Caratheodory metrics. For example, if  $V$  and  $W$  are compact, contact C-C manifolds of dimension  $n = 2m + 1$  admitting a sequence of maps  $f_k: V \rightarrow W$  with  $\text{dil}(f_k) \rightarrow \infty$  and

$$\limsup \frac{\deg(f_k)}{(\text{dil } f_k)^{n+1}} \geq \frac{\text{vol}(V)}{\text{vol}(W)},$$

where “vol” refers to the  $(n + 1)$ -dimensional Hausdorff measure, then the universal covering of  $W$  is isometric to the  $n$ -dimensional Heisenberg group  $H$  with the standard (self-similar!) C-C metric, while  $W$  is locally isometric to  $H$  as well.

Next, one can turn to more general  $V$ , such as solvable Lie groups for instance, where one should not use exhaustions by balls  $B(R_i)$  by rather by domains  $\Omega_i$  having  $\text{vol}_{n-1}(\partial\Omega_i) = o(\text{vol}(\Omega_i))$ . Here, it seems more difficult to identify topological consequences of  $V$ -ellipticity since one does not know if the solvable Lie groups are distinguished by their isoperimetry (see [Va–Sa–Co] for what is known in this regard). Nevertheless, it seems not to be

too hard to show that  $W_0 \# V/\Gamma$  can not be  $V$ -elliptic for nonspherical  $W_0$ . (In fact, this may be expected with more general, e.g. hyperbolic manifolds  $V$  with a suitably defined  $V$ -ellipticity, compare sections 9 $\frac{3}{4}$  in [Gro]PCMD.)

Another interesting line of thought is suggested by Lipschitz maps  $f : V \rightarrow W$  for  $n = \dim(V) < \dim(W)$  with

$$\int_{\Omega_i} f^*(\omega) \geq \text{const vol}(\Omega_i)$$

for  $i \rightarrow \infty$  and for some closed  $n$ -form  $\omega$  in  $W$ . This probably can be carried over pretty far for  $V = \mathbb{R}^n$ , but in more general cases, we are impeded by the absence of (proofs of) suitable  $n$ -dimensional isoperimetric inequalities in non-Euclidean spaces  $W$  of dimension  $> n$  (compare [Gro]CC).

# Chapter 3

## Metric Structures on Families of Metric Spaces

### A. Lipschitz and Hausdorff distance

**3.1. Definition:** The Lipschitz distance between two metric spaces  $X, Y$ , denoted  $d_L(X, Y)$ , is the infimum of the numbers

$$|\log \text{dil}(f)| + |\log \text{dil}(f^{-1})|$$

as  $f$  varies over the set of bi-Lipschitz homeomorphisms between  $X$  and  $Y$ .

By convention, we set  $d_L(X, Y) = \infty$  whenever there is no bi-Lipschitz homeomorphism  $X \rightarrow Y$ . Evidently  $d_L$  is symmetric, satisfies the triangle inequality, and  $d_L(X, Y) = 0$  when  $X, Y$  are isometric. Conversely, we have

**3.2. Proposition:** *Any two compact metric spaces  $X, Y$  satisfying  $d_L(X, Y) = 0$  are isometric.*

**Proof.** For each integer  $n > 0$ , there exists a bi-Lipschitz homeomorphism  $f_n: X \rightarrow Y$  such that  $1 - 1/n \leq \text{dil}(f_n) \leq 1 + 1/n$ . Since the sequence  $(f_n)$  is equicontinuous, it contains a uniformly convergent subsequence, and the limit mapping is necessarily an isometry.

**Example:** If  $X$  is a compact surface of genus  $g > 1$ , the Lipschitz distance defines a metric on its moduli space, viewed as the space of Riemannian metrics of curvature  $-1$ , modulo the group of diffeomorphisms of  $X$ .

**3.3.** We now define a distance between metric spaces that are not necessarily homeomorphic, using the classical notion of Hausdorff distance (cf. [Berger]<sub>Cours</sub> or [Rinow], §7). Recall that for two subsets  $A, B$  of a metric space  $Z$ , this is defined as

$$d_H^Z(A, B) = \inf\{\varepsilon > 0 : B \subset U_\varepsilon(A) \text{ and } A \subset U_\varepsilon(B)\},$$

where  $U_\varepsilon(A) = \{z : d(z, A) \leq \varepsilon\}$ . It is a classical fact (and easy to check) that  $d_H^Z$  is a metric on the space of compact subsets of  $Z$ .

**3.4. Definition:** The Hausdorff distance between two metric spaces  $X, Y$ , denoted  $d_H(X, Y)$ , is defined as the infimum of the numbers

$$d_H^Z(f(X), g(Y))$$

for all metric spaces  $Z$  and isometric embeddings  $f, g$  of  $X, Y$ , respectively, into  $Z$ .

**Remarks:** (a) If  $X, Y$  are compact, then  $d_H(X, Y) < \infty$ . To see this, it suffices to embed  $X$  and  $Y$  into their union, equipped with a metric  $d$  that restricts to the given metrics on  $X, Y$  and satisfies  $d(x, y) = \sup(\text{diam}(X), \text{diam}(Y))$  for  $x \in X$  and  $y \in Y$ .

(b) Two metric spaces with finite diameter can be separated by zero Hausdorff distance without being isometric, as, for example, in the case of  $[0, 1]$  and  $\mathbb{Q} \cap [0, 1]$ .

(c) Even for very simple domains in  $\mathbb{R}^n$ , the Hausdorff distance is not realized by embeddings into Euclidean space. Indeed, if  $A = \{a_1, a_2, a_3\}$  is an equilateral triangle of edge 1 and  $B$  consists of a point, then  $d_H(A, B) = 1/2$ , although any isometric embeddings  $f, g$  of  $A, B$  into  $\mathbb{R}^n$  satisfy

$$d_H^{\mathbb{R}^n}(f(A), g(B)) > \frac{1}{\sqrt{3}}.$$

 (d<sub>+</sub>) Here is a sleeker definition of a distance. Consider surjective maps  $\varphi$  and  $\psi$  from the disjoint union  $Z = X \sqcup Y$  to  $X$  and  $Y$ , respectively, and let  $d_X^*$  and  $d_Y^*$  be the functions on  $Z \times Z$  induced from  $\text{dist}_X$  and  $\text{dist}_Y$  by these maps. Then take the sup-norm of the difference  $d_X^* - d_Y^*$  on  $Z \times Z$  and the infimum of this norm  $\|d_X^* - d_Y^*\|_{L_\infty}$  over all possible surjective maps  $\varphi$  and  $\psi$ . This infimum defines a metric, say  $d_H^*(X, Y)$ , which obviously satisfies  $\frac{1}{2}d_H \leq d_H^* \leq 2d_H$ . (Notice that one could minimize over all abstract sets  $Z$  and surjective maps  $\varphi: Z \rightarrow X$  and  $\psi: Z \rightarrow Y$ .)

Roughly speaking, the convergence of a sequence  $(X_i)$  of metric spaces with respect to the Hausdorff metric corresponds to Lipschitz convergence of  $\varepsilon$ -nets in the  $X_i$  (cf. 2.14) to an  $\varepsilon$ -net in the limit space. More precisely,

### 3.5. Proposition:

- 
- (a) *If a sequence  $(X_i)$  of metric spaces converges to  $X$  with respect to the Hausdorff distance, then for each  $\varepsilon > 0$  and  $\varepsilon' < \varepsilon$ , every  $\varepsilon'$ -net in  $X$  with strictly positive separation is the limit of a sequence  $(N_i)$  of  $\varepsilon$ -nets in the  $X_i$  with respect to the Lipschitz distance.*
  - (b) *Conversely, if  $\sup(\text{diam}(X_i), \text{diam}(X)) < \infty$ , and if, for each  $\varepsilon > 0$ , there exists an  $\varepsilon$ -net of  $X$  that is the Lipschitz limit of a sequence of  $\varepsilon$ -nets  $N_i \subset X_i$ , then the  $X_i$  converge to  $X$  in the Hausdorff metric.*

**Proof.** (a) By hypothesis, there exists a sequence  $\eta_i$  tending to zero and isometric embeddings  $f_i, g_i$  of  $X, X_i$ , respectively, into a metric space  $Z_i$  such that

$$d_H^{Z_i}(f_i(X), g_i(X_i)) \leq \eta_i.$$

If  $(x_p)_{p \in P}$  is an  $\varepsilon$ -net of  $X$ , then since  $f_i(X) \subset U_{\eta_i}(g_i(X_i))$ , there exist points  $x_p^i$  such that

$$d_H^{Z_i}(f_i(x_p), g_i(x_p^i)) < \eta_i,$$

and since moreover  $g_i(X_i) \subset U_{\eta_i}(f_i(X))$ , the  $(x_p^i)_{p \in P}$  form a  $(\varepsilon + 2\eta_i)$ -net in  $X_i$ . Additionally, we have

$$|d^X(x_p, x_{p'}) - d^{X_i}(x_p^i, x_{p'}^i)| \leq 2\eta_i,$$

which shows that  $(x_p^i)_{p \in P}$  Lipschitz converges to  $(x_p)_{p \in P}$  since  $(x_p)_{p \in P}$  has a strictly positive separation.

(b) Let  $(x_p)_{p \in P}$  be an  $\varepsilon$ -net of  $X$  and  $(y_p^i)_{p \in P} \subset X_i$  a sequence of  $\varepsilon$ -nets that converges to  $X$  with respect to the Lipschitz distance. On the union  $X \cup X_i$ , we define — using the same idea as in Remark 3.4(a) — a metric  $d$  that restricts to the given metrics on  $X$  and  $X_i$  by setting

$$d(x, y) = \inf_{p \in P} d^X(x, x_p) + d^{X_i}(y_p^i, y) + \varepsilon$$

for each  $x \in X$  and  $y \in X_i$ . The only nontrivial step in showing that  $d$  is a metric is to check the inequalities of the form

$$d(x, x') \leq d(x, y) + d(y, x')$$

for  $x, x' \in X$  and  $y \in X_i$ . To this end, we write  $d(x, x') \leq d(x, x_p) + d(x_p, x_q) + d(x_q, x')$  and note that

$$d(x_p, x_q) \leq (1 + \eta_i) d(y_p^i, y_q^i),$$

where  $\eta_i \rightarrow 0$ . For sufficiently large  $i$ , we then have

$$\begin{aligned} d(x, x') &\leq d(x, x_p) + d(y_p^i, y_q^i) + d(x_q, x') + \varepsilon \\ &\leq (d(x, x_p) + d(y_p^i, y)) + (d(y, y_q^i) + d(x_q, x')) + \varepsilon, \end{aligned}$$

which gives the desired inequality. With respect to this metric on  $X \cup X_i$ , we clearly have  $d_H(X, X_i) < 2\varepsilon$ .

An important consequence of Proposition 3.5(a) is the following.

**3.6. Proposition:** *Any two compact metric spaces  $X, Y$  satisfying  $d_H(X, Y) = 0$  are isometric.*

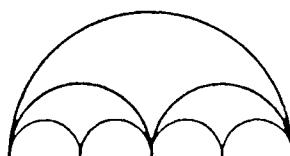
**Proof.** For each integer  $n$  and each  $(1/n)$ -net  $N^{1/n}$  of  $Y$ , there exists a sequence  $N_i^{2/n}$  of  $(2/n)$ -nets in  $X$  such that  $N_i^{2/n}$  Lipschitz converges to  $N^{1/n}$ . For each  $\varepsilon > 0$ , there is an integer  $i_n$  and a mapping  $f_n$  of  $N^{1/n}$  into  $N_{i_n}^{2/n}$  such that both  $f_n$  and  $f_n^{-1}$  have dilatation less than  $1 + \varepsilon$ .

By choosing the nets  $N^{1/n}$  to be nested, we can use a diagonal procedure to obtain a homeomorphism  $g: Y \rightarrow X$  having the same properties, and so the assertion is reduced to the case of Proposition 3.2.

**3.7. Proposition:** *If  $X_n$  are compact metric spaces and  $X_n \xrightarrow{\text{Lip}} X$ , then  $X_n \xrightarrow{\text{Hau}} X$ .*

**Proof.** The statement is an immediate consequence of Proposition 3.5(b).

The converse of this statement is certainly false, even if  $X$  and each  $X_n$  are homeomorphic, as seen in the picture below.



While we cannot expect much stability of topological properties under Hausdorff convergence, certain *metric* properties are stable. More precisely,

**3.8. Proposition:** *If  $X$  is a complete metric space that is the Hausdorff limit of a sequence of path metric spaces, then  $X$  is a path metric space.*

**Proof.** It suffices to apply Theorem 1.8, noting that the existence of approximate midpoints (Property 1.8(1)) is stable under Hausdorff convergence.

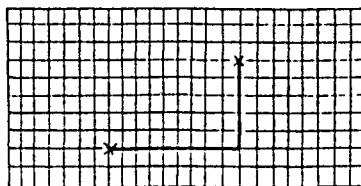
**3.9. Examples:** Let  $(X, d)$  be a metric space, and for  $\lambda > 0$ , let  $\lambda X$  denote the metric space  $(X, \lambda d)$ . If  $\text{diam}(X) < \infty$ , then  $\lambda X$  tends to a point as  $\lambda \rightarrow 0$ .

If  $X_n$  is a sequence of metric spaces and if  $\text{diam}(X_n)$  tends to 0, then for any space  $X$ , we have  $\lim_{n \rightarrow \infty} (X \times X_n) = X$ . More generally, if  $W$  is the total space of a Riemannian fibration (cf. [Ber–Gau–Maz]) whose base  $V$  and fibers are compact, then by change of scale in the fibers we can construct a family  $g_t$  of metrics on  $W$  for which  $\lim_{t \rightarrow 0} (W, g_t) = V$ . This remark applies, for example, to the Hopf fibrations of  $S^{2n+1}$  over  $\mathbb{C}\mathbb{P}^n$  and of  $S^{4n+3}$  over  $\mathbb{H}\mathbb{P}^n$ .

**3.10. Hausdorff convergence and dimension.** The preceding, rather crude examples seem to suggest that dimension is at least lower semi-continuous with respect to Hausdorff convergence. This is not the case, however, as illustrated by a sequence of increasingly fine grids in the square, which, by Proposition 3.5, converge to the square equipped with the norm

$$\|(x, y)\| = |x| + |y|.$$

One can ensure that the dimension of  $X = \lim_H X_n$  does not exceed that of the  $X_n$  by imposing the requirement that the  $X_n$  be convex (if each  $X_n$  is a subset of Euclidean space, then the proof of this assertion is elementary), or by assuming that the  $X_n$  are Riemannian manifolds with uniformly bounded curvature (the subject of Chapter 8).



**3.11.** The examples of sequences of Riemannian manifolds tending to manifold of smaller dimension given in 3.9 are mildly disturbing since the curvatures (seem to) tend to infinity, and one should feel relieved upon learning

that this situation also arises in the case of manifolds with bounded sectional curvature.

### (a<sub>+</sub>) Berger examples

Let  $G$  be a compact Lie group with a left-invariant metric, and let  $H_i$  be a sequence of closed, connected subgroups of fixed dimension  $k$ . Then, the quotient spaces  $X_i = G/H_i$  have curvatures bounded by a constant independent of  $i$ . In fact, the curvature of  $G/H_i$ , being a local quantity, depends *continuously* on the Lie algebra  $\mathfrak{h} = \mathfrak{h}_i \subset \mathfrak{g}$ , where  $\mathfrak{g}$  is the Lie algebra of  $G$ . The family  $\{\mathfrak{h}_i\}$  is precompact, since it is contained in the compact Grassmannian manifold  $\text{Gr}_k(\mathfrak{g})$ . And, if  $\mathfrak{h}_i \rightarrow \mathfrak{h}_\infty \subset \mathfrak{g}$ , then the infinitesimal (and properly understood) local geometry of  $X_i$  converges to that of the local quotient of  $G$  by the connected subgroup  $H_\infty$  corresponding to the (limit) Lie algebra  $\mathfrak{h}_\infty$ . Furthermore, if the subgroup  $H_\infty \subset G$  is closed, then the global quotient  $X_\infty = G/H_\infty$  exists, and obviously  $X_i \xrightarrow{Lip} X_\infty$ . (If  $H_\infty$  is not closed, and this is the case of interest, then one may only speak of the “local quotient” obtained by dividing a small neighborhood  $U$  of the identity in  $G$  into the *connected components* of the intersections of the cosets of  $H_\infty$  with  $U$ .)

Next, for a *nonclosed*  $H_\infty$ , we take its closure  $\overline{H}_\infty \subset G$ , which is again a connected Lie group of dimension  $\dim(H_\infty) > k = \dim(H_i)$ , and we observe that the manifolds  $X_i = G/H_i$  Hausdorff-converge to  $X_\infty = G/\overline{H}_\infty$ , where  $\dim(X_\infty) < \dim(X_i)$ . The simplest of these are the *Berger spheres*  $X_i = (SU(2) \times SU(1))/H_i$ , where  $H_i$  are 1-dimensional subgroups (circles) contained in the torus  $SU(1) \times SU(1)$ , such that the limit  $H_\infty$  is dense in this torus. Thus, the limit manifold is the 2-sphere  $S^2 = SU(2)/SU(1)$ , while all  $X_i$  are 3-dimensional. In fact, we may choose  $H_i$  so that their projections to  $SU(1)$  via  $SU(2) \times SU(1) \rightarrow SU(1)$  are injective, and then, clearly, all  $X_i$  are simply connected and in fact are diffeomorphic to  $S^3$ . Here, the local geometries of  $X_i$  converge to that of the product  $S^2 \times \mathbb{R}$ , while globally the  $X_i$  converge to  $S^2$ . Each  $X_i \simeq S^3$  is Hopf-fibered over  $S^2 = SU(2)/SU(1)$ , with the circle fibers of length  $\ell_i \rightarrow 0$ . If we restrict the fibrations  $X_i$  to a fixed disk  $D^2 \subset S^2$ , then the resulting submanifolds  $Y_i \subset X_i$  are diffeomorphic to  $D \times S^1$ , and their universal coverings, diffeomorphic to  $D \times \mathbb{R}$ , Lipschitz-converge to the actual *Riemannian product*  $D \times \mathbb{R}$ , as the group-theoretic picture above shows.

**Exercise:** Exhibit a sequence of spaces  $X_i = (SU(2) \times SU(2))/H_i$  which Hausdorff-converges to  $S^2 \times S^2$ , while their infinitesimal geometries converge to that of  $S^2 \times S^3$ . (One can even make all  $X_i$  diffeomorphic to  $S^2 \times S^3$ .)

**Remark:** The above collapse of  $X_i$  is due to the nonvanishing of  $\pi_2(S^2 \times S^3)$ . In fact, if manifolds  $X_i$  with  $\pi_1(X_i) = 0$  have the property that their infinitesimal geometries converge to that of some  $X$  with  $\pi_1(X) = \pi_2(X) = 0$ , then  $X_i \xrightarrow{\text{Hau}} X$  (see [Che]CFT, [Gro]Stab).

**Exercise:** Let  $\partial$  be a nonvanishing Killing field on a Riemannian manifold  $(X, g)$ , where ‘‘Killing’’ signifies that  $\partial$  locally integrates to an *isometric* action of  $\mathbb{R}$  on  $X$ , or, equivalently, that the Lie derivative  $\partial g$  vanishes. Denote by  $g_\varepsilon$  the Riemannian metrics on  $X$  defined by the conditions that  $g_\varepsilon(\partial, \partial) = \varepsilon^2 g(\partial, \partial)$  and  $g_\varepsilon = g$  on the vectors  $\tau$  orthogonal to  $\partial$ , i.e.,  $g_\varepsilon(\tau, \tau') = g(\tau, \tau')$  for all  $\tau, \tau'$  satisfying  $g(\partial, \tau) = 0$ ,  $g(\partial, \tau') = 0$ . Show that the curvature of  $g_\varepsilon$  remains bounded as  $\varepsilon \rightarrow 0$  on each compact subset in  $X$ . In fact, that local geometry of  $X_\varepsilon = (X, g_\varepsilon)$  converges to that of  $Y \times \mathbb{R}$ , where  $Y$  denotes the local quotient  $X/\mathbb{R}$  for the local action of  $\mathbb{R}$  on  $X$  given by  $\partial$ . Next, assume that  $X$  is a closed manifold and show that  $X_\varepsilon$  Hausdorff-converges as  $\varepsilon \rightarrow 0$  to  $X/H$ , where  $H$  denotes the closure of the  $\mathbb{R}$ -groups defined by  $\partial$  in the full isometry group  $\text{Iso}(X)$  (compare Ch. 8+A). Apply this to the sphere  $S^{2k+1}$  with the field  $\partial$  tangent to the Hopf fibers and show again that the  $\varepsilon$ -shrinking of (the spherical metric along) these fibers leads to the Hausdorff convergence  $S_\varepsilon^{2k+1} \xrightarrow{\text{Hau}} \mathbb{CP}^k$  with local geometries Lipschitz convergent to  $\mathbb{CP}^k \times \mathbb{R}$ . (Compare [Che–Ebin], p. 70, [Che–Gro], and Ch. 8+A).

### (b) Flat manifolds

In terms of the Hausdorff distance, the Mahler compactness theorem (cf. [Cass], p. 137) states that the closure of the space of flat  $n$ -tori  $\mathbb{T}^n = \mathbb{R}^n/\Lambda$  consists of all flat tori of dimension less than or equal to  $n$ . The limit of a sequence  $\mathbb{T}_i^n = \mathbb{R}^n/\Lambda_i$  has dimension  $n$  if and only if the numbers  $c(\Lambda_i) = \inf\{|\lambda| : \lambda \in \Lambda_i \setminus \{0\}\}$  (in Riemannian terms,  $c(\Lambda_i)$  is twice the radius of injectivity of  $\mathbb{T}_i^n$ ) has a strictly positive lower bound.

If we now consider the closure of the space of flat  $n$ -manifolds, we obtain certain quotients  $\mathbb{R}^k/\Gamma$ , where  $k \leq n$  and  $\Gamma$  is a discrete group of isometries of  $\mathbb{R}^k$  that may have fixed points. This phenomenon already occurs for  $n = 2$ .

Moreover, every singular path metric space of the form  $\mathbb{R}^k/\Gamma$  is the limit of a sequence of flat manifolds of dimension  $n(\Gamma)$ . To see this, it suffices to construct (by elementary means) an extension of  $\Gamma$  by a lattice that acts without fixed points on some  $\mathbb{R}^n$  and then to tend the lengths of its generators to zero.

These examples illustrate that in order to ensure that a sequence of Riemannian  $n$ -manifolds converges to an  $n$ -manifold, a reasonable hypothesis

is provided by a uniform lower bound on the injectivity radii. In Chapter 8, we see several results of this sort, as well as more precise information as to the singularities that can appear in the limit space when the injectivity radii tend to zero.

**3.11 $\frac{1}{2}_+$  The Hausdorff moduli space.** The Hausdorff metric allows us to bring all metric spaces together. For example, the set  $\mathcal{X}_c$  of isometry classes of compact metric spaces has an interesting geometry with respect to the Hausdorff metric  $d_H(X, Y)$  for  $X, Y \in \mathcal{X}_c$ . It is easy to see that  $\mathcal{X}_c$  is a complete, contractible metric space, in which the (isometry classes of) finite spaces  $X$  form a dense subset. (It is not locally compact; in fact, the space of continuous functions on  $[0, 1]$  admits a topological embedding into  $\mathcal{X}_c$ .) One can also make a moduli space of isometry classes of noncompact spaces  $X$  lying within a finite Hausdorff distance from a given  $X_0$ , e.g.,  $X_0 = \mathbb{R}^n$ . Such moduli spaces are also complete and contractible.

**On the functoriality of  $X_i \rightsquigarrow \lim_H X_i$ .** The limit space, whenever it exists, is defined only up to isometry, and morphisms (e.g., isometric or, say, Lipschitz maps)  $X_i \rightarrow X'_i$  do not pass, *a priori*, to any limit maps  $\lim_H X_i \rightarrow \lim_H X'_i$ . But this can be remedied by a more functorial definition of the limit (see 3.29). To clarify the idea of functoriality, we suggest the following:

**Exercises:** (a) Suppose that  $X_i \xrightarrow{\text{Hau}} X$ ,  $X'_i \xrightarrow{\text{Hau}} X'$  and there exist isometric embeddings  $X_i \rightarrow X'_i$  for all  $i = 1, 2, \dots$ . Then there exists an isometric embedding  $X \rightarrow X'$ , provided that  $X'$  is *compact*.

(b) If  $X_i \xrightarrow{\text{Hau}} X$  and all  $X_i$  are *homogeneous*, (i.e., the isometry group of  $X_i$  is transitive on  $X_i$  for every  $i$ ), then  $X$  is also homogeneous provided that it is a locally compact space, decomposable into a union of countably many compact subsets.

(c) Let  $X_i \xrightarrow{\text{Hau}} X$ ,  $X'_i \xrightarrow{\text{Hau}} X'$ , and suppose that there are short surjective maps  $X_i \rightarrow X'_i$  for all  $i$ . Then there is such a map  $X \rightarrow X'$ , provided that  $X$  and  $X'$  are compact.

**3.11 $\frac{2}{3}_+$  Uryson spaces.** A metric space  $Y$  isometrically containing another space  $X$  is called a  *$U_d$ -extension* of  $X$  if  $Y$  isometrically contains every (iso-)metric extension  $X_*$  of  $X$  by a single point,  $X_* = X \sqcup \{x_*\}$ , provided that  $\text{dist}_*(x_*, x) \leq d$  for all  $x \in X$ . This means that for an arbitrary function  $d_*(x) \leq d$  on  $X$  which may serve as a distance function,  $d_*(x) = \text{dist}_*(x_*, x)$  for some metric  $\text{dist}_*$  on  $X_* = X \sqcup \{x_*\}$ , there exists a point  $y = y_{d_*} \in Y$  such that  $\text{dist}_Y(y, x) = d_*(x)$  for all  $x \in X$ .

**Example:** Let  $Y$  be the space of 1-Lipschitz maps  $y : X \rightarrow [0, d]$  with  $\text{dist}(y, y') = \sup_{x \in X} \text{dist}(y(x), y'(x))$ . This is called the  $K_d$ -extension of  $X$ , since  $X$  is isometrically embedded into  $Y$  by the Kuratowski map (see [Kur]), which sends each point  $x_0 \in X$  to the distance function  $y(x) = \text{dist}_X(x, x_0)$ . Clearly, this  $Y$  has the  $U_d$ -property, since one can take  $y_{d_*} = d_*(x) \in Y$ .

A metric space  $Z$  is called  $U_d$ -universal if it  $U_d$ -extends every finite subset  $F \subset Z$ .

(1) **Example:** Start with an arbitrary metric space  $X_0$  and define  $X_0 \subset X_1 \subset X_2 \subset \dots$ , where each  $X_i$  is the  $K_d$ -extension of  $X_{i-1}$ . Then the union  $X_\infty = \bigcup_{i=0}^{\infty} X_i$  is  $U_d$ -universal, since every finite subset is contained in some  $X_{i_0}$  which is  $U_d$ -extended by  $X_{i_0+1}$ .

Here is an obvious, useful

(2) **Lemma:** Let  $Z$  be a  $U_d$ -universal space and let  $A$  be a countable metric space. Then every isometric embedding of a finite subset of  $A$  into  $Z$ , say  $A \supset F_0 \xrightarrow{\varphi} Z$ , extends to an isometric embedding  $A \rightarrow Z$ , provided that  $\text{diam}(A) \leq d$ .

**Proof.** Write  $A = F_0 \cup \{a_1, a_2, \dots\}$  and keep on extending isometric embeddings from  $F_i$  to  $F_{i+1} = F_i \cup \{a_{i+1}\}$ .

(3) **Corollary:** If  $Z$  is complete as well as  $U_d$ -universal, then the isometric extension above is possible from finite subsets to arbitrary second countable metric spaces  $X \supset F_0$ , provided that  $\text{diam}(X) \leq d$ . In particular, every second countable metric space of diameter  $\leq d$  isometrically embeds into  $Z$ .

**Proof.** Use a countable dense subset  $A \subset X$  containing  $F_0$ .

(4) **Theorem (Uryson, see [Ury]):** Every two Polish (i.e., complete, second countable)  $U_d$ -universal spaces  $Z$  and  $Z'$  are isometric.

**Proof.** It suffices to construct increasing sequences of finite subsets  $\dots \subset F_i \subset F_{i+1} \subset \dots$  in  $Z$  and  $\dots \subset F'_i \subset F'_{i+1} \subset \dots$  for  $i = 1, 2, \dots$  and isometries  $F_i \xleftarrow{I_i} F'_i$ , where the  $I_{i+1}$  extend the  $I_i$ , where we want the (necessarily isometric) unions  $F_\infty = \bigcup_{i=1}^{\infty} F_i$  and  $F'_\infty = \bigcup_{i=1}^{\infty} F'_i$  to be dense in  $Z$  and  $Z'$ , respectively. These  $F_i$  are constructed in steps by induction on  $i$ . Given  $F_i$  and  $F'_i$  for an even  $i$ , we add an arbitrary point  $z_{i+1} \in Z$

to  $F_i$  and then extend the isometry  $F_i \xrightarrow{I_i} F'_i$  to  $F_{i+1} = F_i \cup \{z_{i+1}\}$  using the  $U_d$ -universality of  $Z'$ . Similarly, on each *odd* step, we add  $z'_{j+1}$  to  $F'_j$  and extend the isometry  $F'_j \xrightarrow{I_j} F_j$ . Thus, we can arrange our sets to be eventually dense in  $Z$  and  $Z'$ .

**(5) Corollary:** *For each  $d \in [0, \infty]$ , there exists a unique, up to isometry, Polish  $U_d$ -universal space, called the Uryson space  $U_d$ .*

In fact, the uniqueness is shown above, while the existence is obtained with the  $K_d$ -extensions. Namely, the metric completion  $\overline{X}_\infty$  of the union  $X_\infty = \bigcup_{i=0}^\infty X_i$  is  $U_d$ -universal for an arbitrary starting compact metric space  $X_0$ . Here one should note that

(a) if  $X_0$  is compact, then so are its  $K_d$ -extensions for  $d < \infty$  (by the Ascoli theorem) and consequently the union  $X_\infty$  and its completion  $\overline{X}_\infty$  are second countable,

(b) the  $U_d$ -property of a space implies that of its metric completions. In fact, *if a complete metric space  $Y$  admits a dense  $U_d$ -universal subspace, then  $Y$  is  $U_d$ -universal.*

**Proof.** It is obvious that  $Y$  is *approximately  $U_d$ -universal*. This means that for each finite subset  $F \subset Y$ , every  $\varepsilon > 0$  and an arbitrary potential distance function  $d_*$  on  $F$ , there exists  $y \in Y$  such that

$$|\text{dist}(y, f) - d_*(f)| \leq \varepsilon$$

for all  $f \in F$ . (This is seen by  $\varepsilon$ -approximating  $F$  by a finite subset in the dense subspace and appealing to the  $U_d$ -universality of the latter.) But since  $Y$  is complete, *the approximate  $U_d$ -universality implies the actual one* as follows. We assume without loss of generality that  $d_*(f) \geq \delta > 0$  for all  $f \in F$  and we find points  $y_1, \dots, y_i, \dots$  in  $Y$  by induction on  $i$  such that

$$(i) \quad |\text{dist}(f, y_i) - d_*(f)| \leq \delta 2^{-i}, \text{ and}$$

$$(ii) \quad \text{dist}(y_j, y_{j+1}) \leq \delta 2^{-j+2} \text{ for } j = 2, \dots, i.$$

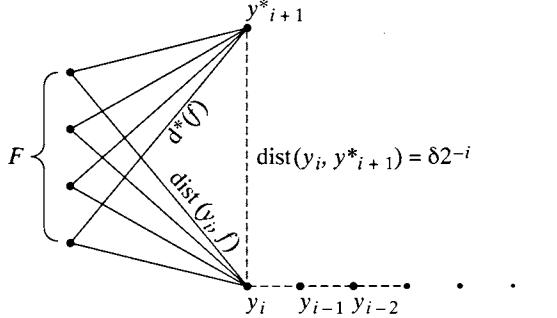
In fact, assume we have already found such  $y_1, \dots, y_i$ , let  $F_i = F \cup \{y_1, \dots, y_i\}$ , adjoin an extra (abstract) point, say  $y_{i+1}^*$  to  $F_i$ , and define a metric  $\text{dist}_*$  on  $F_{i+1}^* = F_i \cup \{y_{i+1}^*\}$ , such that

$$\text{dist}_*|_{F_i} = \text{dist}_Y|_{F_i}, \tag{*}$$

$$\text{dist}_*(f, y_{i+1}^*) = d^*(f), \tag{**}$$

$$\text{dist}_*(y_{i+1}^*, y_i) = \delta 2^{-i}. \quad (***)$$

To do this, we observe that the conditions  $(*) - (***)$  define *metrics* on  $F_i \subset F_{i+1}^*$  and on  $F \cup \{y_i, y_{i+1}^*\} \subset F_{i+1}^*$ , where the triangle inequality for the latter trivially follows from  $(i)$ .



Since these metrics agree on the intersection

$$F_i \cap (F \cup \{y_i, y_{i+1}^*\}) = F \cup \{y_i\},$$

there exists a metric  $\text{dist}_*$  on  $F_{i+1}^* = F_i \cup (F \cup \{y_i, y_{i+1}^*\})$  extending these metrics on  $F_i$  and  $F \cup \{y_i, y_{i+1}^*\}$ .

Now, we use the approximate  $U_d$ -property and extend the embedding  $F_i \subset Y$  to an  $\varepsilon_i$ -isometric embedding  $F_{i+1}^* \rightarrow Y$  with a sufficiently small  $\varepsilon_i$ , say  $\varepsilon_i \leq \delta 2^{-i-1}$ . This means that the distance function from  $y_{i+1}$  (coming from  $y_{i+1}^*$ ) to each point in  $F_i \subset Y$  is  $\varepsilon_i$ -close to the distance  $\text{dist}_*$  from  $y_{i+1}^*$  to this point; therefore,  $(**)$  yields

$$|\text{dist}(f, y_{i+1}) - d^*(f)| \leq \varepsilon_{i+1} \leq \delta 2^{-i-1},$$

for  $f \in F$ , while  $(***)$  implies that

$$\text{dist}(y_{i+1}, y_i) \leq \delta 2^{-i} + \varepsilon_{i+1} \leq \delta 2^{-i+1}.$$

This tells us that the relations  $(i)$  and  $(ii)$  are extended from  $i$  to  $i+1$  and thus we get our infinite sequence  $y_1, \dots, y_i, y_{i+1}, \dots$  satisfying  $(i)$  and  $(ii)$  for  $i = 1, 2, \dots$ . This converges (due to  $(ii)$  and the completeness of  $Y$ ) to the required (because of  $(i)$ )  $y$ .

**Remark:** My attention was recently drawn to Uryson's spaces by A. Vershik, who warmed up my enthusiasm by suggesting the following.

- I. A possible relation between the Uryson spaces  $U_d$  and the Hausdorff moduli space.

- II. Identifying the isometry group of  $U_d$  by some intrinsic (universal) property (compare Exercise (a) below).
- III. Raising the question of the existence of nice (?) measures on  $U_d$  and/or finding a meaningful counterpart of  $U_d$  in the category of metric spaces with measures.

**Exercises:** (a) By adjusting the proof of (4), show that the isometry group is transitive on  $U_d$ . Moreover, it is transitive on mutually isometric  $r$ -tuples of points in  $U_d$  (as are the isometry groups of  $\mathbb{R}^n$  and  $S^n$ ). Notice that  $U_d$  contains proper subsets isometric to itself and so not every isometry between subsets in  $U_d$  isometrically extends to  $U_d$ , but this is true for compact subsets in  $U_d$  (see below).

(b) Show that the  $U_d$ -universality for finite subsets in a complete space  $X$  implies the  $U_d$ -universality for all compact subsets in  $X$ . (*Hint:* Argue as in the derivation of  $U_d$  from approximate  $U_d$ .)

(b') Show that for every pair of isometric compact subsets  $A$  and  $B$  in  $U_d$ , there exists an isometry of  $U_d$  moving  $A$  to  $B$  which agrees with a given isometry  $A \rightarrow B$ .

(c) Construct the Uryson space  $U_{d=\infty}$  by using  $\dots \subset X_i \subset X_{i+1} \subset \dots$ , where  $X_{i+1}$  is the  $K_i$ -extension of  $X_i$ .

(d) Use homotheties in the spaces of functions  $y(x) \mapsto ty(x) \in X_{i+1}, x \in X_i$  and thus obtain homotheties of  $U_d = X_\infty$ , say  $\varphi_t : U_d \rightarrow U_d$ , shrinking  $U_d$  to a (given) point for  $t = 0$  and having the images  $\varphi_t(U_d) \subset U_d$  isometric to  $U_{td} \subset U_d$ . In particular,  $U_d$  is contractible. It is also a path metric space with infinitely many shortest paths between every pair of points (Uryson). And the homothety above selects particular geodesics  $t \mapsto \varphi_t(x)$ ,  $t \in [0, 1]$ , from all  $x \in U_d$  to  $x_0 = \varphi_0(U_d)$ .

(e) (Uryson) Show that the spheres of radius  $d'$  in  $U_d$  are isometric to  $U_{d'}$ .

**Question to the reader:** Do you find this huge  $U_d$  ugly, or, on the contrary, quite beautiful? (A couple of good theorems would make it more respectable in any case.)

There is a discrete version of  $U_d$  which may feel more palatable to some people. Namely, we stick to *countable* spaces  $X$  with *integer* valued metrics  $\text{dist} : X \times X \rightarrow \mathbb{Z}_+$ . The corresponding universal space, say  $U_d^\mathbb{Z}$  comes as  $X_\infty = \bigcup_{i=0}^\infty X_i$ , where  $X_0$  is finite, and  $X_{i+1}$  consists of integer-valued (1-Lipschitz if you wish) functions  $X_i \rightarrow [0, d]$ . (We need a variable  $d$ , say  $d = i$ , in order to arrive at  $U_\infty^\mathbb{Z}$ .)

The isometry groups of  $U_d^{\mathbb{Z}}$  is uncountable for all  $d \geq 1$ . In fact, it contains the full permutation group of a countable set. To see this, observe that the construction of  $X_{\infty}$  can start with an arbitrary countable  $X_0$  if  $X_{i+1}$  consists, by definition, of  $\mathbb{Z}_+$ -valued functions  $y$  on  $X_i$ , such that  $y(x) = \text{dist}_{X_i}(x_0, x)$  for some  $x_0 = x_0(y) \in X_i$ , and *all but finitely many*  $x \in X_i$  (which keeps  $X_{i+1}$  countable). Thus, the isometry group of  $X_0$  acts on  $X_{\infty}$  and one may take  $X_0$  with  $\text{dist}(x, x') = 1$  for all  $x \neq x'$ . (Or one can play with  $X_0 = X_{\infty}$ .)

It would be interesting to find a nice embedding  $\text{Isom } U_d^{\mathbb{Z}} \subset \text{Isom } U_d$  and to look at the quotient space. Also, it seems logical to represent  $U_{\infty}$  as some kind of limit of  $\varepsilon U_{\infty}^{\mathbb{Z}}$ , but I do not know if this makes sense (compare 3.29 $_{\frac{1}{2},+}$ ).

Finally, we can ask for which geometric and combinatorial structure (e.g., colored graphs, hypergraphs, etc.) Uryson type universal objects exist. One may try here a construction of such a space by gluing together representatives of our spaces along isomorphic subsets in the spirit of the definition of the Hausdorff moduli space. For example, let us construct  $U_{\infty}^{\mathbb{Z}}$  in this way. First, we enumerate all *finite*  $\mathbb{Z}_+$ -metric spaces, say they are  $X_1, X_2, \dots$ . Then we construct finite spaces  $Y_{i+1}$  by induction as follows. Take  $Y_i$  and consider all isometries between subsets  $Y' \subset Y_i$  and subsets in the spaces  $X_1, \dots, X_{i+1}$ . Enumerate these isometries by  $\nu = 1, 2, \dots, N = N(i)$  and glue the spaces  $X_{j(\nu)}$  to  $Y_i$  successively according to these isometries  $I_{\nu}$ . Thus, we get  $Y_i \subset Y_i^1 \subset \dots \subset Y_i^{\nu} \subset \dots Y_i^N = Y_{i+1}$ , where  $Y_i^{\nu+1}$  is obtained from  $Y_i^{\nu}$  by gluing  $X_{j(\nu)}$  to it along some  $X_{\nu}' \xrightarrow{I_{\nu}} Y_{\nu}' \subset Y_i \subset Y_i^{\nu}$ . Clearly, the union  $Y_{\infty} = \bigcup_{i=0}^{\infty} Y_i$  is  $U_{\infty}$ -universal and thus isometric to  $U_{\infty}^{\mathbb{Z}}$ .

**Exercises:** (a) Make a similar construction for  $U_{\infty}$  by applying some gluings to a (universal) *continuous family* of compact metric spaces (similar to the Hausdorff moduli space).

(b) Consider the space of compact subsets in  $U_{\infty}$  with the Hausdorff metric, call it  $U_{\infty}^+$ , and show that  $U_{\infty}^+ / \text{Isom}(U_{\infty})$  is isometric to the Hausdorff moduli space  $\mathcal{H}_c$  (thus vindicating Vershik's idea). The above makes  $U_{\infty}^+$  a good candidate for the universal ramified covering  $\tilde{\mathcal{X}}_c$  of  $\mathcal{X}_c$  indicated below.

(c) Show that every second countable metrizable group  $G$  admits a free isometric action on  $U_{\infty}$ .

(d) Vershik also suggested that Uryson spaces come from suitable measures on the space  $M_{\infty}$  of infinite symmetric matrices viewed as random

metrics on  $\mathbb{N}$  (compare 3.39(4)). Another way to put it is that a (sufficiently) random metric space is  $U_\infty$ . To make this precise, consider the space  $M_\infty$  of metrics on  $\mathbb{N} = \{1, 2, \dots\}$  and let  $\mu$  be a probability measure on  $M_\infty$  with the following properties.

- (1)  $\mu$  is invariant and ergodic under the group of permutations of  $\mathbb{N}$  with finite support.
  - (2) the natural projection (push-forward) of  $\mu$  to the space  $M_r$  of metrics on  $\{1, 2, \dots, r\}$  is a Borel measure whose support equals all of  $M_r$  for every  $r = 1, 2, \dots$ . Then almost all (for this  $\mu$ ) metrics  $m \in M_\infty$  are approximately  $U_\infty$ -universal, and hence the completion of  $(\mathbb{N}, m)$  is isometric to  $U_\infty$  for almost all  $m \in M_\infty$ . Checking everything is just another exercise for the reader.
- (e) Define  $U_d$ -universality in the category of spaces with a free proper isometric action of a locally compact, second countable group  $G$ . Show the existence of these spaces and prove that they are all isometric to  $U_\infty$ .
- (f) Return to the construction of  $U_d$  as the tower of the  $K_d$ -extensions and find other (stronger) structures on these (besides the metric) with the transitive automorphism group. (I have not fully solved this problem.)

**3.11<sub>4+</sub><sup>3</sup> Orbit structures in the moduli spaces.** Let us look at the Hausdorff moduli space  $\mathcal{X}_c$  in a small neighborhood  $U$  of some space  $X_0 \in \mathcal{X}_c$  which has a nontrivial isometry group  $G_0$ . If  $G_0$  is a finite group, then a (sufficiently small!)  $U$  can be rather naturally represented as  $\tilde{U}/G_0$ , where  $\tilde{U}$  consists of isometry classes of suitably marked spaces  $X$  close to  $X_0$  as explained in the simplest case in 3.32. Ideally, we want to have some natural “universal branched covering”  $\tilde{\mathcal{X}}_c \rightarrow \mathcal{X}_c$  which has “Iso( $X$ )-ramification” at each  $X \in \mathcal{X}_c$  such that (the local isometries of)  $\tilde{\mathcal{X}}_c$  keep track of isometric (even better, Lipschitz) maps  $X \rightarrow X'$  for all  $X, X' \in \mathcal{X}_c$ . But I do not know if there is a suitable realization of this idea, for example, in the spirit of the theory of stacks, giving some  $\tilde{\mathcal{X}}_c$  smaller than  $U_\infty$ .

**Motivating Example:** Consider the space of all Riemannian manifolds diffeomorphic to a fixed  $V$ . Then this space  $\mathcal{X} = \mathcal{X}_V$  equals  $\mathcal{G}/\text{Diff}(V)$ , where  $\mathcal{G}$  denotes the space of all Riemannian metrics on  $V$ . Consider the subset  $\mathcal{X}_0 = \mathcal{G}_0/\text{Diff}(V)$  corresponding to Riemannian manifolds  $(V, g)$  with *trivial* isometry groups and equip  $\mathcal{X}_0$  with the Lipschitz (instead of Hausdorff) metric. Then  $\mathcal{G}_0 \rightarrow \mathcal{X}_0$  constitutes a principle  $\text{Diff}(V)$ -fibration, and  $\mathcal{G}_0$  is a contractible space for  $\dim(V) \geq 2$ . Thus, the fundamental group  $\Gamma$  of  $\mathcal{G}_0$  equals  $\pi_0(\text{Diff}(V))$ . So, we can define  $\tilde{\mathcal{X}}$  as the metric completion of

the universal covering  $\tilde{\mathcal{X}}_0$  and observe that  $\Gamma$  isometrically acts on  $\tilde{\mathcal{X}}$  with  $\tilde{\mathcal{X}}/\Gamma = \mathcal{X}$ .

## B. The noncompact case

**3.12.** When dealing with noncompact spaces, it is convenient to work in the category of pointed spaces. The Lipschitz and Hausdorff distances between pointed metric spaces are defined as in 3.1 or 3.3, except that only pointed bi-Lipschitz homeomorphisms and isometric embeddings are allowed.

The connection between convergence and pointed convergence can be described as follows:

**3.13. Proposition:** *Let  $(X_n, a_n)$  and  $(X, a)$  be complete, locally compact path metric spaces. In order for  $\lim_{\text{H}}(X_n, a_n) = (X, a)$ , it is necessary and sufficient that the sequence of closed balls  $B(a_n, r)$  Hausdorff converges to  $B(a, r)$  uniformly in  $r$ .*

**Proof.** Apply “abstract nonsense” (à la Zorn); in any case, we will not have use for this proposition in the remainder of the book.

The uniformity in the  $r$  condition is actually unreasonably strong, since it does not even allow the sphere  $S^n(r)$  to converge to  $\mathbb{R}^n$  as  $r \rightarrow \infty$ . For complete, locally compact path metric spaces, we will use the following:

**3.14. Definition:** We will say that  $(X_n, a_n)$  tends to  $(X, a)$  in the Hausdorff (resp. Lipschitz) sense if, for each  $r > 0$ , the ball  $B(a_n, r + \varepsilon_n)$  Hausdorff (resp. Lipschitz) converges to  $B(a, r)$  for some sequence  $(\varepsilon_n)$  tending to 0.

For a pointed space  $(X, a)$ , the study of  $\lambda X = (X, \lambda \text{dist}_X)$  (cf. 3.9) for large  $\lambda$  amounts to looking at a neighborhood of  $a$  under a magnifying glass. For example,

**3.15. Proposition:** *Let  $(V, g)$  be a Riemannian manifold with  $g$  continuous. For each  $v \in V$ , the spaces  $\lambda(V, v)$  Lipschitz converge as  $\lambda \rightarrow \infty$  to the tangent space  $(T_v V, 0)$  with its Euclidean metric  $g_v$ .*

**Proof<sub>+</sub>**. Start with a  $C^1$  map  $(\mathbb{R}^n, 0) \rightarrow (V, v)$  whose differential is isometric at 0. The  $\lambda$ -scalings of this provide almost isometries between large balls in  $\mathbb{R}^n$  and those in  $\lambda V$  for  $\lambda \rightarrow \infty$ .

**Remark:** In fact, we can *define* Riemannian manifolds as locally compact

path metric spaces that satisfy the conclusion of Proposition 3.15.

Evidently, it is more interesting to tend  $\lambda$  to zero, in which case the limit space (if it exists) will depend on the global properties of the original space (cf. [Pr]). A trivial, yet fundamental remark is that for each metric  $d$  on  $\mathbb{R}^n$  arising from a norm, we have  $\lim \lambda \mathbb{R}^n = \mathbb{R}^n$  as  $\lambda \rightarrow 0$ . This is a special case of the following observation:

**3.16. Proposition:** *Let  $V$  be a path metric space whose fundamental group is isomorphic to  $\mathbb{Z}^n$ , and let  $\tilde{V}$  be its universal cover, equipped with the natural length structure. For  $\tilde{v} \in \tilde{V}$ , the sequence of homothetic spaces  $2^{-k}(\tilde{V}, \tilde{v})$  Hausdorff converges to  $(\mathbb{R}^n, 0)$  equipped with a metric arising from a (possibly non-euclidean) norm.*

The norm  $\|\cdot\|$  described in the proposition is obtained as follows. By Proposition 2.11, there exists a limit-norm, denoted  $\|\cdot\|^{lim}$ , on the group  $\pi_1(V, v_0)$  having the property that if  $q \in \mathbb{Z}$ , then  $\|q\alpha\|^{lim} = |q|\|\alpha\|^{lim}$ . By means of an isomorphism, we equip the subgroup  $\mathbb{Z}^n$  of  $\mathbb{R}^n$  with this norm and extend by homogeneity to  $\mathbb{Q}^n$  and then by continuity to  $\mathbb{R}^n$ .

**Proof.** Choose an isomorphism  $\varphi: \mathbb{Z}^n \rightarrow \Gamma = \pi_1(V, v_0)$  and let  $\alpha_1, \dots, \alpha_n$  be the image of the canonical basis of  $\mathbb{Z}^n$ . We will use the same notation for an element of  $\Gamma$  and the deck transformation of  $\tilde{V}$  that it induces. Fix  $\varepsilon > 0$  and an integer  $k_0$  such that

$$2^{-k_0} \left( \sum_{i=1}^n \text{length}(\alpha_i) + \text{diam}(V) \right) < \varepsilon$$

and such that the subgroup  $2^{-k_0}\mathbb{Z}^n$  is an  $\varepsilon$ -net of  $(\mathbb{R}^n, \|\cdot\|)$ . Set  $N = 2^{-k_0}\mathbb{Z}^n$  and for  $k \geq k_0$ , define  $\varphi_k: N \rightarrow \tilde{V}$  by

$$\varphi_k(2^{-k_0}(x_1, \dots, x_n)) = \prod_{i=1}^n (\alpha_i^{x_i})^{2^{k-k_0}} \cdot \tilde{v}.$$

Then  $N_k = \varphi_k(N)$  is an  $\varepsilon$ -net in  $2^{-k}\tilde{V}$ ; indeed, if  $\alpha \in \Gamma$ , then

$$\begin{aligned} d(\alpha\tilde{v}, N_k)_{\tilde{V}} &= d(\tilde{v}, \alpha^{-1}N_k)_{\tilde{V}} \\ &\leq d\left(\tilde{v}, \prod_{i=1}^n \alpha_i^{(2^{k-k_0}[x_i 2^{k_0-k}] - x_i)} \cdot \tilde{v}\right)_{\tilde{V}} \\ &\leq 2^{k-k_0} \left( \sum_{i=1}^n \text{length}(\alpha_i) \right), \end{aligned}$$

so that if  $\tilde{x} \in \tilde{V}$  we have

$$\begin{aligned} d(\tilde{x}, N_k)_{\tilde{V}} &\leq d(x, \tilde{\Gamma}\tilde{v})_{\tilde{V}} + d(\Gamma\tilde{v}, N_k)_{\tilde{V}} \\ &\leq \text{diam}(V) + 2^{k-k_0} \left( \sum_{i=1}^n \text{length}(\alpha_i) \right) \\ &< 2^k \varepsilon, \end{aligned}$$

whence  $d(\tilde{x}, N_k)_{2^{-k}\tilde{V}} < \varepsilon$ . Finally, we verify that if  $x, y \in N$ , then the sequence  $d(\varphi_k(x), \varphi_k(y))_{2^{-k}\tilde{V}}$  tends to  $\|y - x\|$  as  $k \rightarrow \infty$ . Let  $x = 2^{-k_0}x', y = 2^{-k_0}y'$  so that

$$\begin{aligned} d(\varphi_k(x), \varphi_k(y))_{2^{-k}\tilde{V}} &= 2^{-k} d \left( v, \left( \prod_{i=1}^n \alpha_i^{x'_i - y'_i} \right)^{2^{k-k_0}} \cdot \tilde{v} \right)_{\tilde{V}} \\ &\rightarrow 2^{-k_0} \left\| \prod_{i=1}^n \alpha_i^{x'_i - y'_i} \right\|^{lim} \\ &= \|x - y\| \end{aligned}$$

as  $k \rightarrow \infty$ . In other words,  $\text{dil}_{(x,y)}(\varphi_k) \rightarrow 1$  as  $k \rightarrow \infty$ , and so, since  $N \cap B(0, r)$  is finite, we have

$$\text{dil}(\varphi_k|_{N \cap B(0, r)}) \rightarrow 1 \quad \text{and} \quad \text{dil}(\varphi_k^{-1}|_{N_k \cap B(v, r)}) \rightarrow 1,$$

which proves that the restrictions of the  $N_k$  to radius- $r$  balls Lipschitz converge to  $N \cap B(0, r)$ . Thus,  $2^{-k}V$  converges to  $(\mathbb{R}^n, \|\cdot\|)$ .

**Remarks<sub>+</sub>:** (a) What one truly needs is not  $\pi_1(V) = \mathbb{Z}^n$  but rather a surjective homomorphism  $\pi_1(V) \rightarrow \mathbb{Z}^n$  giving us a Galois  $\mathbb{Z}^n$ -cover  $\tilde{V}$  of  $V$  to which the proposition above applies.

(b) Typically, there is *no Lipschitz* convergence  $2^{-k}\tilde{V}$  to  $\mathbb{R}^n$ , since  $\tilde{V}$  may even be nonhomeomorphic to  $\mathbb{R}^n$ , as in the case of the  $\mathbb{Z}^n$ -covering of the connected sums  $V = T^n \# V_0$ , where  $V_0$  is not a homotopy sphere. In fact, if the convergence is Lipschitz, then obviously  $\tilde{V}$  is isometric to  $(\mathbb{R}^n, \|\cdot\|^{lim})$ , and since  $\tilde{V}$  is Riemannian, it is isometric to the Euclidean space  $\mathbb{R}^n$ .

(c) **D. Burago's theorem.**  $\tilde{V}$  lies within a finite Hausdorff distance from  $(\mathbb{R}^n, \|\cdot\|^{lim})$  (see [Bur]PM and 2.C'1 in [Gro]AI).

The key step in the proof is the following property of the lengths of the shortest loops in  $(V, v_0)$  representing the elements  $\alpha$  of  $\mathbb{Z}^n$  (where  $\pi_1(V) = \mathbb{Z}^n$ , or, more generally, we are given an epimorphism  $\pi_1(V) \rightarrow \mathbb{Z}^n$ )

$$\text{length}(\alpha) \leq \frac{1}{2} \text{length}(2\alpha) + \text{const}.$$

**Problem<sub>+</sub>:** What are the possible limit norms for Riemannian manifolds  $\tilde{V}$  with  $\mathbb{Z}^n$ -periodic metrics? This question has been addressed by V. Bangert and more recently by Burago and Ivanov, who conjecture that these norms cannot be smooth unless  $\tilde{V} = \mathbb{R}^n$ . However, we don't even know if there are non-Euclidean  $\tilde{V}$  with Euclidean limit norms.

**3.17.** If  $X = \lim_{\lambda \rightarrow 0} \lambda V$ , then clearly  $X$  is conical, i.e., isometric to  $\lambda X$  for all  $\lambda \neq 0$ . The simplest path metric space after  $\mathbb{R}^n$  having this property is the 3-dimensional Heisenberg group  $\mathbb{H}^3$ , equipped with its Carnot metric (cf. 1.18).

If  $a, b, c$  are generators of its Lie algebra  $\mathfrak{h}_3$  such that  $[a, c] = [b, c] = 0$  and  $[a, b] = c$ , and  $f_\lambda$  is defined by  $f_\lambda(a, b, c) = (\lambda a, \lambda b, \lambda^2 c)$ , then one can see that for  $x, y \in \mathbb{H}^3$  and  $\lambda > 0$ , we have  $d(f_\lambda(x), f_\lambda(y)) = \lambda d(x, y)$ . The limit space is given by

**3.18. Proposition:** Let  $g$  be the left-invariant Riemannian metric on  $\mathbb{H}^3$  with respect to which  $a, b, c$  are orthonormal. As  $\lambda \rightarrow 0$ , the metric  $\lambda g$  tends to the Carnot metric defined by  $g$  and the left-invariant plane field spanned by left-translates of  $\{a, b\}$ . Consequently, the Carnot space  $(\mathbb{H}^3, \lim_{\lambda \rightarrow 0} \lambda g)$  is indeed conical, and  $(\mathbb{H}^3, \lambda g)$  Hausdorff-converges to  $(\mathbb{H}^3, \lim_{\lambda \rightarrow 0} \lambda g)$ .

**Proof.** Apply the same principle as in Proposition 3.15, using the fact that if the elements of  $\mathbb{H}^3$  are represented by matrices of the form

$$\begin{pmatrix} 1 & u & w \\ 0 & 1 & v \\ 0 & 0 & 1 \end{pmatrix},$$

then the metric  $g$  is given by  $du^2 + dv^2 + (dw - u\,dv)^2$ .

**3.18<sub>2+</sub><sup>1</sup> The Pansu theorem.** Let  $V$  be a Riemannian manifold admitting a discrete isometric action of a nilpotent group  $\Gamma$  with compact quotient. It is easy to see that the family  $\lambda V$  is precompact (compare Ch. 5A-B), and thus there exists a (pointed) Hausdorff limit  $X = \lambda_i V$  for a sequence  $\lambda_i \rightarrow 0$ . Such an  $X$  is, in fact, a nilpotent Lie group equipped with a Carnot metric which admits a nontrivial self-similarity, i.e., an isometry  $X \rightarrow \alpha X$  for  $\alpha \neq 1$  which is moreover a group isomorphism. All this is easy; what is nontrivial is the following

**Convergence theorem (see [Pan]<sub>CBC</sub>).** The spaces  $\lambda V$  converge to  $X$  as  $\lambda \rightarrow 0$  in the pointed Hausdorff topology.

## C. The Hausdorff–Lipschitz metric, quasi-isometries, and word metrics

The Lipschitz metric introduced earlier is too restrictive because of the simple fact that two spaces must be homeomorphic in order for their Lipschitz distance apart to be finite. Thus, on the one hand, the Hausdorff distance is not in general finite for unbounded spaces and is therefore too restrictive “at infinity,” as we have observed in Proposition 3.13, whereas the Lipschitz distance can be rendered infinite by a small singularity at finite distances. This is why we need a distance that combines the two.

**3.19. Definition:** The *Hausdorff–Lipschitz distance* between two metric spaces  $X, Y$ , denoted  $d_{\text{HL}}(X, Y)$ , is the infimum of the numbers

$$d_{\text{H}}(X, X_1) + d_{\text{L}}(X_1, Y_1) + d_{\text{H}}(Y_1, Y),$$

where  $X_1, Y_1$  are arbitrary metric spaces. One says that  $X$  and  $Y$  are *quasi-isometric* if  $d_{\text{HL}}(X, Y) < \infty$ .

Before presenting some properties of this metric, we first describe two means for defining a distance on a finitely-generated discrete group.

**3.20. Definition:** Let  $\Gamma$  be a discrete group of finite type and  $\{\gamma_i\}$  a finite set of generators for  $\Gamma$ . For each  $\alpha \in \Gamma$ , we define  $\|\alpha\|_{\text{alg}}$  as the smallest length of a word in the  $\gamma_i$  and their inverses that represents  $\alpha$ . The function  $\|\cdot\|_{\text{alg}} : \Gamma \rightarrow \mathbb{R}_+$  is a norm on  $\Gamma$ , i.e., a function satisfying

1.  $\|\alpha\|_{\text{alg}} = 0$  if and only if  $\alpha = 1$ .
2.  $\|\alpha + \beta\|_{\text{alg}} \leq \|\alpha\|_{\text{alg}} + \|\beta\|_{\text{alg}}$ .
3.  $\|\alpha^{-1}\|_{\text{alg}} = \|\alpha\|_{\text{alg}}$ .

We call  $\|\cdot\|_{\text{alg}}$  the *algebraic (word) norm associated with the set  $\{\gamma_i\}$  of generators*. It is the largest norm that assumes the value 1 on each  $\gamma_i$ .

**3.20<sub>2+</sub>** **Changing generators.** If we replace  $\gamma_i$  by another finite system of generators  $\gamma'_j$ , then the resulting norm remains *equivalent* to the old one, i.e.,

$$c\|\cdot\|_{\text{alg}}^{\text{old}} \leq \|\cdot\|_{\text{alg}}^{\text{new}} \leq c'\|\cdot\|_{\text{alg}}^{\text{old}}.$$

In fact, this is (obviously) true when  $c = (\sup_i \|\gamma_i\|^{\text{new}})^{-1}$  and when  $c' = \sup_j \|\gamma'_j\|^{\text{old}}$ , and a more general geometric equivalence is stated in Proposition 3.22 below.

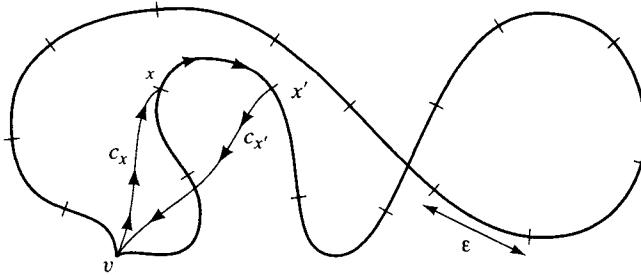
**3.21. Definition:** Let  $V$  be a compact Riemannian manifold and let  $\tilde{V}$  be its universal cover, so that the fundamental group  $\Gamma$  of  $V$  acts by isometries on  $\tilde{V}$ . The *geometric norm* associated with a point  $v \in V$  is defined as

$$\|\alpha\|_{\text{geo}} = d(\tilde{v}, \alpha\tilde{v})_{\tilde{V}},$$

where  $\tilde{v}$  is any point lying over  $v$ . This norm equals the length of a shortest loop representing  $\alpha$ .

**3.22. Proposition:** For each  $v \in V$ , the fundamental group  $\pi(V, v)$  is generated by a finite number of classes represented by loops based at  $v$  having length at most  $2 \text{diam}(V)$ . All of the norms (a) associated with finite sets of generators and (b) associated with points of  $V$  are equivalent.

**Proof.** For each element  $\alpha$  of the fundamental group  $\Gamma$  of  $V$ , we choose a representative loop  $a$  based at  $v \in V$ . For  $\varepsilon > 0$  we divide each loop  $a$  into pieces of length less than  $\varepsilon$  and connect each of the endpoints  $x$  thus obtained to  $v$  by a minimizing arc  $c_x$ . Then  $a$  is homotopic to the product of the loops  $c_x a|_{[x, x']} c_{x'}^{-1}$  based at  $v$ , where  $(x, x')$  denotes a consecutive pair of endpoints along  $a$ .



Thus, we have found a system of generators for  $\Gamma$  represented by loops of length less than  $2 \text{diam}(V) + \varepsilon$ . The set of lengths of minimizing geodesics is discrete (cf. 1.13), however, and so for sufficiently small  $\varepsilon$ , the interval  $(2 \text{diam}(V), 2 \text{diam}(V) + \varepsilon)$  contains no length of a closed, minimizing geodesic based at  $v$ . Consequently, each of the curves we have constructed is homotopic to a curve of length at most  $2 \text{diam}(V)$ .

We begin by showing that the algebraic norms associated with two finite sets  $G^1, G^2$  of generators are equivalent. Let  $\|\cdot\|^1, \|\cdot\|^2$  denote these norms, and set  $S^1 = \sup\{\|\alpha\|^2 : \alpha \in G^1\}$ . Then  $(1/S^1)\|\cdot\|^2$  is a norm on  $\Gamma$  that assumes values less than 1 on  $G^1$ . Thus,

$$(1/S^1)\|\cdot\|^2 \leq \|\cdot\|^1.$$

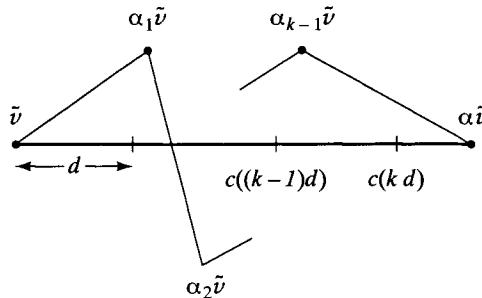
Given a point  $\tilde{v} \in \tilde{V}$ , let  $G$  be a finite set of generators of  $\Gamma$  containing all elements of  $\Gamma$  for which  $\|\alpha\|_{\text{geo}} \leq 3 \text{diam}(V) = 3d$  for the norm associated with the point  $v$ . Again, the norm  $(1/3d)\|\cdot\|_{\text{geo}}$  assumes values less than 1 on the generators belonging to  $G$  and is therefore bounded above by the algebraic norm  $\|\cdot\|_{\text{alg}}$  associated with  $G$ . Conversely, suppose we are given an element  $\alpha$  of  $\Gamma$  and a minimizing geodesic  $c$  from  $\tilde{v}$  to  $\alpha\tilde{v}$  in  $\tilde{V}$  parametrized by arc length. Then the points  $\tilde{v} = c(0), c(d), c(2d), \dots, c(kd)$  (where  $k = [d^{-1}\|\alpha\|_{\text{geo}}]$ ) are spaced by  $d$ . For each  $i \leq k$ , there exists an element  $\alpha_i$  of  $\Gamma$  such that  $d(c(id), \alpha_i\tilde{v}) \leq d$ . Thus,  $d(\alpha_i\tilde{v}, \alpha_{i+1}\tilde{v}) \leq 3d$ , and so

$$\alpha_i^{-1}\alpha_{i+1} \in G$$

and

$$\|\alpha\|_{\text{alg}} \leq \|\alpha_1\|_{\text{alg}} + \sum_{i=1}^{k-2} \|\alpha_i^{-1}\alpha_{i+1}\|_{\text{alg}} + \|\alpha_{k-1}^{-1}\alpha\|_{\text{alg}} \leq k \leq \frac{1}{d}\|\alpha\|_{\text{geo}}.$$

We conclude that  $d\|\cdot\|_{\text{alg}} \leq \|\cdot\|_{\text{geo}} \leq 3d\|\cdot\|_{\text{alg}}$ .



Every norm on a group induces a metric by the formula

$$d(\alpha, \beta) = \|\alpha^{-1}\beta\| = \|\beta^{-1}\alpha\|.$$

The above-mentioned property can be reformulated thus: Each of the metric spaces  $(\Gamma, \|\cdot\|_{\text{alg}})$  or  $(\Gamma, \|\cdot\|_{\text{geo}})$  lie within a finite Lipschitz distance from one another.

**3.23. Proposition:** *If two manifolds  $V_1, V_2$  have isomorphic fundamental groups, then  $d_{\text{HL}}(\tilde{V}_1, \tilde{V}_2) < \infty$ . If two groups  $\Gamma_1, \Gamma_2$  act on the same manifold  $V$  and are cocompact in  $V$  (i.e., the quotients  $V/\Gamma_i$  are compact), then  $d_{\text{HL}}(\Gamma_1, \Gamma_2) < \infty$ .*

**Proof.** This follows from the fact that, in both cases,  $d_{\text{H}}(\tilde{V}, \Gamma\tilde{v}) < \infty$ .

**Example:** The fundamental groups of compact hyperbolic  $n$ -manifolds are quasi-isometric.

**Example:** If  $\tilde{V}$  is the universal cover of a compact manifold  $V$  whose fundamental group is isomorphic to the discrete Heisenberg group,

$$\left\{ \begin{pmatrix} 1 & m & n \\ 0 & 1 & p \\ 0 & 0 & 1 \end{pmatrix} : m, n, p \in \mathbb{Z} \right\},$$

then  $d_{\text{HL}}(\tilde{V}, \mathbb{H}^3) < \infty$ , where  $\mathbb{H}^3$  is again the continuous 3-dimensional Heisenberg group.

**3.24+ The word metric.** The metric on  $\Gamma$  associated to an algebraic norm is called a *word metric*. Word metrics associated to different finite generating subsets of  $\Gamma$  are bi-Lipschitz equivalent, i.e., the identity map  $(\Gamma, \text{dist}_1) \leftrightarrow (\Gamma, \text{dist}_2)$  is bi-Lipschitz, as follows from the equivalence of the norms. This suggests the geometric study of finitely generated groups, where we are interested in the those properties which are invariant under bi-Lipschitz maps. In fact, it is more convenient to relax “bi-Lipschitz convergence” to “quasi-isometry,” since  $\Gamma = \pi_1(V)$  is *quasi-isometric to*  $\tilde{V}$ , as we have just seen, rather than bi-Lipschitz equivalent to it. On the other hand, since the word metrics are discrete, one can think that the two notions coincide for groups, i.e.,

$$d_{\text{HL}}(\Gamma_1, \Gamma_2) < \infty \Rightarrow d_L(\Gamma_1, \Gamma_2) < \infty,$$

but this question remains unsettled at the present date. Observe that the existence of a quasi-isometry between metric spaces  $X_1$  and  $X_2$  is equivalent to the existence of bi-Lipschitz equivalent *nets*  $\Delta_i \subset X_i$ , where  $\Gamma \subset X$  is called a net if  $\text{dist}(x, \Delta) \leq \text{const}$  for all  $x \in X$ . Furthermore, one can insist that these nets are *separated* (where  $\Delta \subset X$  is said to be separated or *uniformly discrete* if  $\text{dist}(\delta_1, \delta_2) \geq \varepsilon > 0$  for all  $\delta_1$  and  $\delta_2$  in  $\Delta$ ), since every net lies within a finite Hausdorff distance from a separated net. Now the algebraic problem above can be stated in the following geometric terms:

*For which metric spaces  $X$  are every two separated nets in  $X$  bi-Lipschitz equivalent, i.e., have  $d_L < \infty$ ?*

It is obvious that all separated nets in  $\mathbb{R}$  are bi-Lipschitz, but this is unknown in  $\mathbb{R}^n$  for  $n \geq 2$ . On the other hand, the question is resolved for free groups by Papasoglu. In particular, *the free groups on  $p$  and  $q$  generators are mutually bi-Lipschitz equivalent for all  $q \geq p \geq 2$*  (see [Pap]HTBE).

The key property of the free groups  $\Gamma_p$ ,  $p \geq 2$ , is *nonamenability* (see Ch. 6). In fact, it is not very hard to show that *for every net  $\Delta$  in a*

*nonamenable group  $\Gamma$ , there exists a bijective map  $f : \Gamma \rightarrow \Delta$  such that  $\text{dist}(\gamma, f(\gamma)) \leq \text{const}^1$ .*

**Exercise:** Show that the above fails to be true in  $\Gamma = \mathbb{Z}^n$ , as well as in any finitely generated amenable group.

The notion of quasi-isometry, originated in the work by Mostow and then Margulis (see [Most]), generalizes the purely algebraic notion of *commensurability* of discrete groups, which means the existence of isomorphic subgroups  $\Delta_1 \subset \Gamma_1$  and  $\Delta_2 \subset \Gamma_2$  of finite index. It is believed that for many classes of groups, quasi-isometry implies commensurability, but one must be aware of the following:

**3.25+ Counterexamples:** (a) Let  $\Gamma_1$  and  $\Gamma_2$  be cocompact discrete subgroups in a given connected Lie group  $G$  (or, more generally, in a compactly generated group). Then, clearly,  $\Gamma_1$  and  $\Gamma_2$  are quasi-isometric, but one knows that they do not have to be commensurable, say for  $G = SL_2(\mathbb{C})$ .

(b) Here is a more dramatic example. Let  $\Gamma_p$  denote the fundamental group of an oriented surface of genus  $p$  and let  $\Gamma'_p$  be the fundamental group of the unit tangent bundle of this surface. Then, for  $p \geq 2$ ,  $\Gamma'_p$  is quasi-isometric (and hence bi-Lipschitz) to  $\Gamma_p \times \mathbb{Z}$ , as was (independently) observed by S. Gersten and D. Epstein. (Note that this is false for  $p = 1$ , since  $\Gamma'_p$  is a nilpotent nonvirtually abelian group.)

**Proof.** For  $p \geq 2$ , the group  $\Gamma_p$  is quasi-isometric to the hyperbolic plane  $H$ , while  $\Gamma'_p$  is quasi-isometric to the universal cover of the unit tangent bundle  $UH$ . The cover  $\widetilde{UH}$  constitutes a (topologically trivial)  $\mathbb{R}$ -fibration over  $H$  with connection given by Levi-Civita on  $H$ . Now fix a point  $v_0 \in H$  and bring each fiber  $\widetilde{UH}_v \subset \widetilde{UH}$ ,  $v \in H$ , to  $v_0$  via parallel transport along the geodesic segment between  $v$  and  $v_0$ . This gives us a projection  $\varphi : \widetilde{UH} \rightarrow \mathbb{R} = \widetilde{UH}_{v_0}$  which is Lipschitz, since the holonomy around every geodesic triangle  $\Delta(v_0, v, v')$  in  $H$  is bounded by its area and thus by *const.*  $\text{dist}(v, v')$ , since geodesics issuing from  $v_0$  exponentially diverge. It follows that the map  $f : \widetilde{UH} \rightarrow H \times \mathbb{R}$  satisfying  $f(\tilde{u}) = (p(\tilde{u}, \varphi(\tilde{u})), \varphi(\tilde{u}))$ , where  $p$  is the projection  $\widetilde{UH} \rightarrow H$ , is Lipschitz, and since it is isometric on the fibers  $\widetilde{UH}_v = \mathbb{R} \rightarrow v \times \mathbb{R}$ , it is bi-Lipschitz as well.

**3.26+ Exercises:** (a) Generalize the above to the universal covering of a circle bundle with connection over a complete, simply connected manifold

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<sup>1</sup> “Exotic” nets in  $\mathbb{R}^n$  are constructed in the recent papers [McM1] and [Bur-Klei], and nonamenable spaces are treated in [Why], [Bog], and [Necr].

with negative curvature  $\leq -\kappa < 0$ , provided that the connection in question has bounded curvature form (e.g., coming from a compact manifold  $V$  via a covering  $X \rightarrow V$ ).

(b) Let  $X$  be a *Hermitian* symmetric space with nonpositive curvature, and let  $U \rightarrow X$  be the circle bundle associated to the *canonical bundle* of  $X$ , i.e.,  $\bigwedge^n T(X)$ , where  $n = \dim_{\mathbb{C}} X$  and  $\bigwedge^n$  denotes the (top) exterior power. Show that  $\tilde{U}$  is bi-Lipschitz equivalent to  $X \times \mathbb{R}$  and apply this to central extensions of cocompact discrete groups acting on  $X$ . *Hint:* Observe that the curvature form  $\omega$  of  $U$  vanishes on flat geodesic subspaces in  $X$ .

(c) **A dynamical criterion for quasi-isometry:**  $\Gamma_1$  and  $\Gamma_2$  are quasi-isometric if and only if there exists a metric space  $X$  admitting mutually commuting cocompact discrete actions of  $\Gamma_1$  and  $\Gamma_2$ .

**Hint:** The “if” part is straightforward. To prove “only if,” construct  $X$  as the space of  $\lambda$ -Lipschitz maps  $f: \Gamma_1 \rightarrow \Gamma_2$ , where  $\lambda$  is a fixed large number, and where  $f$  admits *quasi-inverse*  $\lambda$ -Lipschitz maps  $g: \Gamma_2 \rightarrow \Gamma_1$ , i.e., such that  $f \circ g$  and  $g \circ f$  lie within a finite distance from the identity maps  $\Gamma_2 \rightarrow \Gamma_2$  and  $\Gamma_1 \rightarrow \Gamma_1$ , respectively (where  $\text{dist}(\varphi, \psi) \stackrel{\text{def}}{=} \sup_{\gamma} \text{dist}(\varphi(\gamma), \psi(\gamma))$ ).

**Example:** If  $\Gamma_1 = \Gamma_2 = \Gamma$ , one can use  $\Gamma$  for  $X$  with the left and right action of  $\Gamma$  on itself.

**References:** Geometric group theory has recently exploded into a vast field, see [Groups].

## D<sub>+</sub> First-order metric invariants and ultralimits

**3.27. Hausdorff convergence via  $K_r(X)$ .** We recall that the subsets  $K_r(X)$  in the space  $M_r$  of symmetric  $(r \times r)$ -matrices are comprised of the distances between all  $r$ -tuples of points in  $X$  (compare 1.19<sub>+</sub>). We begin with the following elementary observation.

**3.27<sub>2</sub>**. Two compact metric spaces  $X, Y$  are isometric if and only if  $K_r(X) = K_r(Y)$  for all  $r = 1, 2, \dots$ .

**Proof.** The inclusion  $K_r(X) \subset K_r(Y)$  says that every  $r$ -point subset in  $X$  embeds isometrically into  $Y$ . Since  $X$  and  $Y$  are compact, this property for all  $r = 1, 2, \dots$  implies that  $X$  itself embeds isometrically into  $Y$ , and

similarly,  $Y$  embeds isometrically into  $X$ . Thus,  $X$  is isometric to  $Y$ , since both are compact.

Note that compactness is an essential condition, as the example of  $X = \mathbb{R}$  and  $Y = \mathbb{R}_+$  shows.

Now we can introduce *local* Hausdorff convergence  $X_i \rightarrow Y$  as the convergence of the subset  $K_r(X_i) \rightarrow K_r(Y)$  for every given  $r = 1, 2, \dots$ , where the space of subsets in  $M_r = \mathbb{R}^{r(r-1)/2}$  is given the ordinary Hausdorff metric. Clearly, this new local convergence  $X_i \xrightarrow{H_{\text{loc}}} Y$  implies our old one if the family  $\{X_i\}$  is precompact in the topology of  $d_H$ . On the other hand, any sequence  $X_i$  with  $\text{diam}(X_i) \leq \text{const}$  admits a subsequence, say  $X_j$ , such that  $K_r(X_j)$  Hausdorff-converges to some subset  $N_r \subset M_r$  for each  $r = 1, 2, \dots$  (and the same applies without the bound on the diameter if one speaks of Hausdorff convergence in  $M_r$  on compact subsets). It is not hard to show (an exercise for the reader) that there exists a (nonunique) metric space  $Y$  with  $K_r(Y) = N_r$  for all  $r = 1, 2, \dots$ . In fact, there is a canonical choice of such  $Y$  (explained in 3.29) which absorbs full information on the limit behavior of the geometries of finite subsets in  $X_i$ .

**3.28. First order theory of metric spaces.** Finite configurations of points in  $X$  carry more information than is encoded in  $K_r(X) \subset M_r$ . For example,

$$\text{Rad}(X) \stackrel{\text{def}}{=} \inf_x \sup_y \text{dist}(x, y)$$

cannot be expressed in terms of  $K_r(X)$ . Then one can get even trickier and define something more sophisticated (and ugly) like this:

$$X' = \{x \in X : \sup_y \text{dist}(x, y) \leq 1.1 \text{Rad}(X)\},$$

and  $X'' = (X')'$ ,  $X''' = (X''),  $\dots$ , etc. Then set  $\text{Rad}^{\dots\dots}(X) = \text{Rad}(X^{\dots\dots})$ . The invariants of this type can be expressed with (long) chains of quantifiers  $\exists x \forall y \exists z \dots$ , or set-theoretically as follows. We think of  $K_r$  as an  $M_r$ -valued map in  $r$  variables  $x_1, \dots, x_r$ . If we temporarily fix  $x_1, \dots, x_{r-1}$  and vary  $x = x_r \in X$ , we get a map  $X \rightarrow M_r$  whose image in  $M_r$  is denoted by  $\text{im}_{x_r} K(x_1, \dots, x_r) \in M'_r$ , where  $M'_r$  denotes the power set of  $M_r$ , i.e., the set of subsets in  $M_r$ . Thus, we get an  $M'_r$ -valued function in the variables  $x_1, \dots, x_{r-1}$ , say  $K'_r(x_1, \dots, x_{r-1})$ , and then by repeating the procedure above, we get the  $M''_r = (M'_r)'$ -valued function  $K''_r(x_1, \dots, x_{r-1})$ , then  $K'''_r(x_1, \dots, x_{r-1})$ , etc., terminating with a single point in  $M_r^{(r)}$  denoted by  $K_r^{(r)} \in M_r^{(r)}$ , which conveys the full information on the geometry of  $r$ -tuples of points in  $X$ . Then each space  $M_r^{(i)}$  can be given, by induction$

on  $i$ , the metric corresponding to the Hausdorff distance between subsets in  $M_r^{(i-1)}$ . This gives a (semi-)metric on metric spaces leading to a refinement of the above notion of local Hausdorff convergence.

**Examples:** (a) The spaces  $X = \mathbb{R}$  and  $Y = \mathbb{R}_+$  are distinguishable by 3-point configurations, since every point in  $\mathbb{R}$  can appear as the center of a triple of points isometric to  $\{-1, 0, 1\}$ , while this is not true in  $\mathbb{R}_+$ .

(b) The coverability of  $X$  by, say, 100 balls of given radii can be expressed in terms of the above  $M'_{101}$ .

(c) The metric connectedness of  $X$ , i.e., the existence of chains  $x_1 = x, x_2, \dots, x_r = y$  between each  $x, y \in X$  with  $\text{dist}(x_i, x_{i+1}) < \varepsilon$  for every  $\varepsilon > 0$  can be expressed in terms of (the totality of)  $M'_r$ ,  $r = 1, 2, \dots$ . But, the ordinary topological connectedness seems to be out of the reach of  $M_r^{(i)}$ .

(d) It is not hard to express properties of coverings of  $X$  by finite unions of balls in terms of  $K$ 's, but the full-fledged notion of the topological dimension is beyond  $K_r^{(i)}$ ; the same can be said about the Hausdorff dimension, where the usual definition is even more transcendental.

(e) Start with the real line and attach to it unit segments at the point of a given subset  $V \subset \mathbb{R}$ . For example, take  $V \subset \mathbb{Z} \subset \mathbb{R}$  by choosing the points in  $\mathbb{Z}$  independently at random with probability  $1/2$ . Given two such random subsets  $V, V'$  in  $\mathbb{Z} \subset \mathbb{R}$ , we have two different spaces, say  $X_V$  and  $X_{V'}$  which are obviously nonisometric (use  $K_r^{(2)}$ ) but which cannot be distinguished by sequences of finite measurements. (For example, for each  $x \in X_V$  and every  $R > 0$ , there exists a point  $x' \in X_{V'}$  such that  $x$  and  $x'$  have isometric  $R$ -balls around them. But, if we replace  $\mathbb{R}$  by  $\mathbb{R}_+$ , it is easy to tell  $X_V(\mathbb{R})$  from  $X_{V'}(\mathbb{R}_+)$  by looking at balls). A hierarchy of different systems of invariants is possible in the framework of model theory, but I do not know if anybody has carried out such investigations. On the other hand, one is keen on particular invariants with a geometric flavor to them (see [Grov]MTM). For example, one can take a function  $I$  on  $M_5$  and define

$$\text{Inv}_I(X) = \inf_{x_1} \sup_{x_2} \inf_{x_3} \inf_{x_4} \sup_{x_5} I(K_5(x_1, x_2, x_3, x_4, x_5)).$$

The question is for which  $I$  (if any) one gets something interesting (compare [Grov]CPT, [Grov]MTM).

**3.29. Ultraproducts.** Suppose we have distinguished a class of  $\mathbb{R}$ -valued metric invariants of metric spaces. For example, we could use the above  $\text{In}_I$ , where we allow all bounded, continuous functions  $I$  on  $M_r$ ,  $r = 1, 2, \dots$ ,

and we take arbitrary inf sup sequences. Then we say that a sequence  $X_i$  converges to  $X$  if  $\text{Inv}(X_i) \rightarrow \text{Inv}(X)$  for each invariant Inv from our class. If we want to get away with this, we must face the following problem. Suppose  $\lim_{i \rightarrow \infty} \text{Inv}(X_i)$  exists for each of our Inv. Does there then exist a space  $X$  with these limit invariants and which can therefore be called  $\lim_{i \rightarrow \infty} X_i$ ?

Here is a universal construction. Start with the cartesian product  $Y = \{x_1, x_2, \dots, x_i, \dots\}$  with  $x_i \in X_i$ , where the distance takes values in  $\mathbb{R}_+^\infty$  rather than in  $\mathbb{R}_+$ , namely  $\text{DIST}(\{x_i\}, \{x'_i\}) = \{\text{dist}_{X_i}(x_i, x'_i)\}$ ,  $i = 1, 2, \dots$ . Now we want to pass from sequences  $d_1, d_2, \dots$ , to numbers, i.e., to assign some kind of limit to  $\{d_i\}$  for  $i \rightarrow \infty$ . In other words, we need a suitable projection  $\mathbb{R}_+^\infty \rightarrow \mathbb{R}_+$ , and such is known to exist under the name of *nonprincipal ultrafilters* on the natural numbers. Given such an ultrafilter, say  $\omega$ , we can speak of  $\lim_\omega d_i$  for an arbitrary bounded sequence  $d_i$ , and we define  $\text{dist}_\omega$  on  $Y$  as  $\lim_\omega \text{dist}_{X_i}(x_i, x'_i)$ . Notice that this distance can vanish on some distinct pairs  $(\{x_i\}, \{x'_i\})$  (for example, it is zero if  $x_i = x'_i$  for all but finitely many  $i$ 's) and so we must factor  $Y$  by the  $\text{dist}_\omega = 0$  equivalence relation. The resulting space is our ultraproduct,  $X_\omega$ . (Recall that  $\omega$  can be thought of as a point in the Stone-Čech compactification of  $\mathbb{N}$ , and  $X_\omega$  appears as the limit of the  $X_i$  for  $i \rightarrow \omega$ .)

This definition must be adapted slightly for pointed spaces  $X_i$ , and it becomes particularly useful for defining the *asymptotic cone*  $\text{Con}_\infty(X) = \lim_{\varepsilon \rightarrow 0} \varepsilon X$  as follows (compare [Dri-Wil], [Gro]AI). Fix a point  $x_0 \in X$ , consider the sequences  $x_i$  satisfying  $\text{dist}(x_i, x_0) \leq \text{const } i$ , where the constant can depend on  $\{x_i\}$  (but not on  $i$ , of course!) and set

$$\text{dist}_\omega(\{x_i\}, \{x'_i\}) = \lim_\omega \frac{1}{i} \text{dist}(x_i, x'_i).$$

**3.29<sup>1</sup>/<sub>2</sub> Asymptotic cones of hyperbolic spaces.** Let  $X$  be a complete, simply connected space with negative sectional curvature  $K(X) \leq -\kappa < 0$ . For instance, one can take the hyperbolic plane  $H^2$ , or the  $n$ -dimensional  $H^n$  (including  $n = \infty$ ). Then this  $X$  is *tree-like at infinity* (see [Gro]<sub>HG</sub>), which can be adequately expressed by saying that  $\text{Con}_\omega(X)$  is a *tree*, i.e., a 1-dimensional contractible path metric space, where, moreover, there is a *unique* topological segment containing two given distinct points as its endpoints. Notice that this tree has uncountable branching at every point. (In fact, and this is especially clear for  $X = H^n$ , the isometry group is transitive on  $\text{Con}_\omega(X)$ .) Yet, this is not as bad as it may seem, and this limit tree turns out to be quite useful for the study of *hyperbolic groups*  $\Gamma$ , which can actually be defined by requiring  $\text{Con}_\omega(\Gamma)$  to be a tree for the word metric in  $\Gamma$  (see [Paul]). Also, there are nonhyperbolic spaces (especially

groups) with reasonable (e.g., finite-dimensional)  $\text{Con}_\omega$ . This is probably the case for all connected Lie groups,  $p$ -adic Lie groups and lattices (i.e., finite co-volume subgroups) in them (compare [Gro]AI).

## **E<sub>+</sub>** Convergence with control

### **3.30. Examples of regular and irregular Hausdorff convergence.**

The ideal situation is where the Hausdorff convergence  $X_i \xrightarrow{\text{Hau}} X$  reduces to Lipschitz convergence  $X_i \xrightarrow{\text{Lip}} X$  such that the implied bi-Lipschitz homeomorphisms  $f_i : X \rightarrow X_i$  satisfy  $f_i(x) \xrightarrow{\text{Hau}} x$  for all  $x \in X$ . (Notice that the Hausdorff convergence  $X_i \xrightarrow{\text{Hau}} X$  allows us to define convergence  $x_i \xrightarrow{\text{Hau}} x \in X$  for sequences  $x_i \in X_i$ .) This, of course, is an exceptionally rare case, and we would be satisfied by just having continuous maps (preferably homeomorphisms)  $f_i : X_i \rightarrow X$  satisfying  $f(x_i) \xrightarrow{\text{Hau}} x$  for all  $x \in X$ .

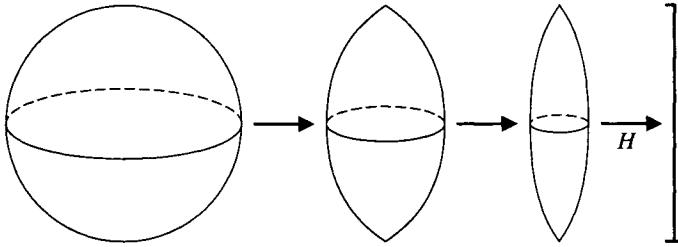
Another class of examples is suggested by the degeneration of algebraic and semialgebraic subsets in  $\mathbb{R}^n$ . Namely, if a sequence of such subsets  $X_i$  Hausdorff-converges to  $X$ , and the degrees of  $X_i$  are bounded by a constant independent of  $i$ , then  $X$  is also semialgebraic of  $\dim(X) \leq \sup_i \dim(X_i)$  and  $\deg(X) \leq \sup_i \deg(X_i)$ . Furthermore, the degeneration occurring in the course of the convergence is no worse than in the following cases:

- (a) the circle  $x^2 + y^2 = \varepsilon^2$  converges to a single point as  $\varepsilon \rightarrow 0$ ;
- (b) the hyperbola  $xy = \varepsilon$  converges to the pair of lines  $xy = 0$ ;
- (c) let  $X$  be an arbitrary semialgebraic, e.g., piecewise linear subset in  $\mathbb{R}^n$  of positive codimension and let  $X_\varepsilon$  be the boundary of the  $\varepsilon$ -neighborhood of  $X_\varepsilon$ . Then  $X_\varepsilon \rightarrow X$  as  $\varepsilon \rightarrow 0$ , where  $X$  can consist of several pieces of different dimensions, and where one may use the induced path metric in  $X_\varepsilon$  for  $\text{codim}(X) \geq 2$ .

Next, one can look at convergent Riemannian manifolds,  $X_i \xrightarrow{\text{Hau}} X$ , where  $\dim X_i = n$ . A basic example is where we are given an isometric action of a compact, connected Lie group  $G$  on  $X_0$ , and we collapse  $X_0$  to  $X = X_0/G$  by shrinking the original Riemannian metric  $g_0$  on  $X$  along the orbits. Specifically, if the orbits have equal dimension and  $X_0$  fibers over  $X$ , then we split  $g_0$  as  $g_0 = g_0^{\text{vert}} + g_0^{\text{hor}}$  according to the splitting of the tangent bundle  $T(X_0)$  into the parts which are normal and tangent to the orbits. Then, we take

$$X_i = (X_0, g_i = i^{-1}g_0^{\text{vert}} + g_0^{\text{hor}})$$

and observe that  $g_0^{\text{hor}}$  is induced by the projection  $X_0 \rightarrow X = X_0/G$ ; thus,  $X_0 \xrightarrow{\text{Hau}} X$  (compare 3.9). In general, if the orbits are not equidimensional, we apply the shrinking to the maximal open subset  $U_0 \subset X_0$  where the orbits have the maximal dimension. The resulting Riemannian metric on  $U_0$  gives us a (singular) path metric on all of  $X_0$  as  $\text{codim}(X_0 \setminus U_0) \geq 2$  (since  $G$  is connected) and  $U_0$  is connected. Thus, we get the convergence  $X_i \xrightarrow{\text{Hau}} X$  anyway. For example,  $S^2$  with the obvious  $S^1$ -action collapses to the segment  $[0, \pi]$ .



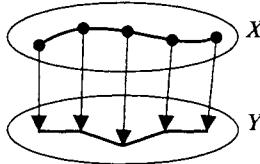
Now, we do not introduce any group action but just assume that  $X_i \xrightarrow{\text{Hau}} X$ , while the sectional curvatures of  $X_i$  are uniformly bounded,  $|K(X_i)| \leq \text{const}$ . Then again, the picture is very similar to the above group actions. Namely, either there is *no collapse*, i.e.,  $\dim(X) = n = \dim(X_i)$ , and then  $X_i \xrightarrow{\text{Lip}} X$  or, if  $\dim(X) < n$ , then the convergent manifolds  $X_i$  can be visualized as fibrations over  $X$  with possibly singular fibers. (See Ch. 8+). In fact, much of this stratified fibration picture persists under the one-sided curvature bound  $K(X_i) \geq -\text{const}$  and something even remains for  $\text{Ricci}(X_i) \geq -\text{const}$  especially if  $X_i$  are *Einstein* manifolds. (See [Che–Col], [Col]ARC).

Finally we turn to “bad” examples, among which the foremost is given by discrete  $\varepsilon$ -nets  $X_\varepsilon^\circ$  in  $X$  which Hausdorff-converge to  $X$ . One can turn such a net into a path metric space, namely a graph  $X_\varepsilon^1$  with an  $\varepsilon$ -net  $X_\varepsilon^\circ \subset X$  serving as the vertex set of  $X_\varepsilon^1$ , and where every two points  $x$  and  $y$  in  $X_\varepsilon$  within distance  $\delta \leq \delta_\varepsilon$  are joined by an edge of length  $\delta$ . We chose  $\delta_\varepsilon \rightarrow 0$  for  $\varepsilon \rightarrow 0$  with  $\varepsilon/\delta_\varepsilon \rightarrow \infty$  and then, clearly,  $X_\varepsilon^1 \xrightarrow{\text{Hau}} X$  provided that  $X$  is a path metric space. Here, we achieved connectedness of the spaces  $X_\varepsilon$  approximating  $X$  but paid by high nonsimple connectedness. Furthermore, if one prefers manifolds, one can replace  $X_\varepsilon^1$  by surfaces: just embed each  $X_\varepsilon^\circ$  into  $\mathbb{R}^3$  and take the boundary of a small  $\varepsilon'$ -neighborhood for an approximating surface (compare [Cass]).

One may perform further surgery, say fill in all small triangles of edges in the graphs  $X_\varepsilon^1$  by actual 2-dimensional triangles, thus obtaining a se-

quence of 2-polyhedra  $X_\varepsilon^2 \rightarrow X$ . If  $X$  is locally simply-connected, then the fundamental groups of  $X_\varepsilon^2$  for small  $\varepsilon$  are naturally isomorphic to  $\pi_1(X)$  (compare below).

**3.31. Remark on surjectivity**  $\pi_1(X_\varepsilon) \rightarrow \pi_1(X)$ . If two path metric spaces, say  $X$  and  $Y$ , are  $\varepsilon$ -Hausdorff close, then every path in  $X$  can be (nonuniquely) moved to  $Y$  by subdividing it into segments of length  $\leq \varepsilon$ , moving the division points to nearest points in  $Y$  and joining them in  $Y$  by minimal geodesic segments (of length  $\leq 3\varepsilon$ ).



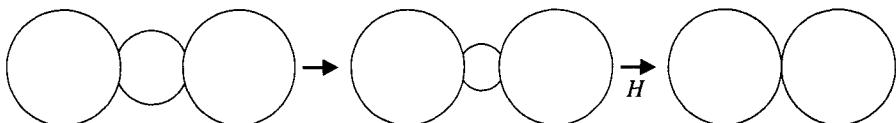
(Recall that  $X$  and  $Y$  may be isometrically embedded into some metric space  $Z$ , where their ordinary Hausdorff distance becomes  $\leq \varepsilon$  and ‘‘moving points by  $\varepsilon$ ’’ refers to the metric on  $X \cup Y$  induced from  $Z$ ). Now let  $X_\varepsilon \xrightarrow{\text{Hau}} Y$  for  $\varepsilon \rightarrow 0$ , take a closed loop  $\alpha$  in  $Y$ , move it to  $X_\varepsilon$  and then go back from  $X_\varepsilon$  to  $Y$ . The resulting loop  $\alpha'$  in  $Y$  is about  $\varepsilon$ -close to  $\alpha$  and so it is homotopic to  $\alpha$  if  $Y$  is locally simply connected. Thus, the convergence  $X_\varepsilon \xrightarrow{\text{Hau}} X$  ensures an *epimorphism*  $\pi_1(X_\varepsilon) \rightarrow \pi_1(X)$  for  $\varepsilon \rightarrow 0$ .

This argument applies both ways to the above  $X_\varepsilon^2 \rightarrow X$ , since the spaces  $X_\varepsilon^2$  are uniformly locally simply connected in an obvious sense, and so  $\pi_1(X_\varepsilon^2) \simeq \pi_1(X)$  for small  $\varepsilon$ .

**3.32. Hausdorff moduli spaces of graphs and surfaces.** We have just seen that every compact path metric space appears as a limit of graphs (i.e., 1-complexes), but the topological type of these  $X_\varepsilon^1$  goes to infinity for  $\varepsilon \rightarrow 0$ . Now let us look at the finite 1-complexes  $X$  of bounded topological type, where *topological complexity*  $\text{Top}(X)$  is defined as the minimal number of edges needed to present (or subdivide)  $X$ .

Here is an obvious but pleasant fact.

**Observation:** Let  $X_\varepsilon \xrightarrow{\text{Hau}} X$  for  $\varepsilon \rightarrow 0$ , where  $X_\varepsilon$  are graphs satisfying  $\text{Top}(X_\varepsilon) \leq t < \infty$ . Then  $X$  is also a graph with  $\text{Top}(X) \leq t$ .

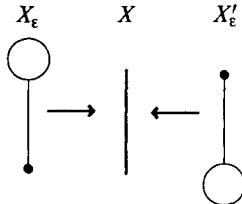


(Notice that the above remains valid when  $X_\varepsilon$  and/or  $X$  are allowed to be noncompact.)

**Corollary:** *The space  $\mathcal{X} = \mathcal{X}(1, t)$  of finite connected graphs  $X$  with  $\text{Top}(X) \leq t$  is complete with respect to the Hausdorff topology. Furthermore, the subset  $\mathcal{X}_\ell \subset \mathcal{X}$  consisting of  $X$  with length  $\ell$  is compact.*

Notice that  $\mathcal{X}$  is naturally a cone, where  $\mathbb{R}_+$  acts by  $X \mapsto \lambda X = (X, \lambda \cdot \text{dist}_X)$  for  $\lambda \in \mathbb{R}_+$ , and each  $\mathbb{R}_+$  orbit intersects  $\mathcal{X}_\ell$  for  $\ell > 0$  at a single point. Also observe that  $\mathcal{X}$  admits a natural finite cell decomposition: each cell consists of the set of mutually homeomorphic graphs  $X$ .

To better understand  $\mathcal{X}$ , one should observe that it carries a natural *orbispace* structure, i.e., for each point  $X \in \mathcal{X}$ , there exists a neighborhood  $\mathcal{U} \subset \mathcal{X}$  of  $X$  which is represented as  $\tilde{U}/G$  for some metric space  $\tilde{U}$  with an isometric action of a finite group  $G$  on  $\tilde{U}$ . The group  $G$  here is the isometry group of  $X$  (where one should be aware of  $X = S^1$  with infinite  $G$  which needs the extra case) and  $\tilde{U}$  is obtained by distinguishing the isometric deformations  $X_\varepsilon$  and  $X'_\varepsilon$  of  $X$  if the implied isometry between  $X_\varepsilon$  and  $X'_\varepsilon$  corresponds to a non-identity in  $G$ .

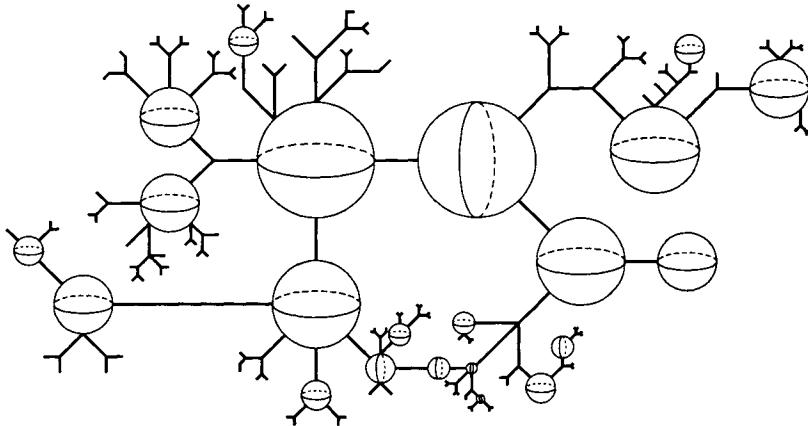


The (suitably defined for orbispaces) *universal covering* of the (slightly modified)  $\mathcal{X}$  plays the key role in the study of the automorphism groups of free groups. (See [Bri–Vog])

**Polyhedra of dimension  $n \geq 2$ .** The topological complexity of spaces  $X$  of dimension  $n > 1$  may increase under Hausdorff limits (see below), but one can bound the *geometric complexity*,  $\text{geo}(X)$ , defined as the minimal number of Euclidean simplices needed to partition  $X$ . (For  $\dim(X) = 1$ , obviously,  $\text{Top}(X) = \text{geo}(X)$ ). Now again, whenever  $X_\varepsilon \xrightarrow{\varepsilon} X$  with  $\text{geo}(X) \leq g$ , we have  $\dim(X) \leq n \leq \dim(X_\varepsilon)$  and  $\text{geo}(X) \leq g$ , but this has little topological significance. (One could measure the complexity in terms of the combinatorial structure of the stratification of our spaces into locally Euclidean strata, keeping an eye on the Bieberbach theorem, which implies that every compact, flat  $n$ -dimensional manifold  $X$  can be triangulated into at most  $g \leq g(n)$  Euclidean simplices). In any case, the corresponding

moduli space  $\mathcal{X}(n, g)$  is a conical space of dimension  $\leq g_1$ , where  $g_1$  is the minimal number of 1-simplices that a Euclidean triangulation of  $X$  with  $\text{geo}(X) \leq g$  can have. In fact,  $X$  lies in  $\mathbb{R}^{g_1}$  as a semialgebraic set. Some fragments of  $\mathcal{X}(2)$  appear in Teichmüller theory, since Riemann surfaces admit piecewise Euclidean metrics with few singular points. Notice that the Teichmüller space itself can be defined as the universal orbispace covering of the Hausdorff space of surfaces of constant curvature  $-1$  and of a fixed genus. Also, topologists have studied the parts of  $\mathcal{X}(n)$  corresponding to polyhedra of a given simple homotopy type, but it is unclear whether there is a meaningful geometric theory of  $\mathcal{X}(n, g)$  for all  $n$ .

**Surfaces of genus  $g$ .** Consider all closed surfaces  $X$  of genus  $g$  equipped with path (e.g., Riemannian) metrics, and look at the Hausdorff completion of the space of these  $X$ 's. If such surfaces Hausdorff-converge to some metric space  $X_\varepsilon \xrightarrow{\text{Hau}} Y$ , then the assumption  $\text{genus}(X_\varepsilon) = g$  severely restricts the topology of  $Y$ . For example, if  $g = 1$ , then the limit may look no worse than the following *bubble (or branching) space*,



In fact, we have the following

**Proposition (Compare [Shio]):** *Every point  $y \in Y$  either admits a neighborhood homeomorphic to  $\mathbb{R}^2$  or  $y$  is a local cut point, i.e.,  $U \setminus \{y\}$  is disconnected for every small neighborhood  $U \subset Y$  of  $y$ .*

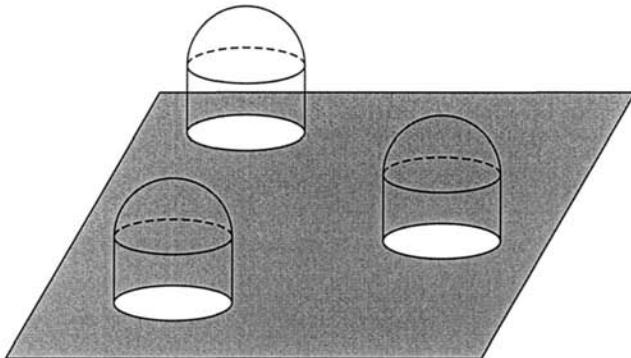
**Sketch of the proof:** Suppose that there is a sequence of closed curves  $C_\varepsilon \subset X_\varepsilon$  such that  $\text{diam}(C_\varepsilon) = \delta_\varepsilon \rightarrow 0$  as  $\varepsilon \rightarrow 0$ , but  $C_\varepsilon$  is nonhomologous to zero in its  $\rho$ -neighborhood in  $X_\varepsilon$  for a fixed  $\rho > 0$ . Then, clearly, the  $C_\varepsilon$  (sub)converge to a local cut point in  $Y$ . So, if  $Y$  has no local cut points, then the surfaces  $X_\varepsilon$  are *controllably locally acyclic*, i.e., there exists a (control)

function  $\rho(\delta)$ ,  $\rho(\delta) \rightarrow 0$  for  $\delta \rightarrow 0$ , such that every closed curve  $C$  in each  $X_\varepsilon$  of diameter  $\leq \delta$  bounds in its  $\rho$ -neighborhood. One knows (see [White]) that  $Y$  is a topological surface in this case, and similarly, every  $U \subset Y$  without local cut points is locally  $\mathbb{R}^2$ . (The topology of the cut points in  $Y$  is rather transparent here, since  $Y$  is locally simply connected by an easy argument similar to the proof of surjectivity  $\pi_1(X_\varepsilon) \rightarrow \pi_1(X)$ .)

The above suggests nice properties of the Hausdorff (orbi-)space of surfaces of genus  $g$  reminiscent of the moduli spaces of holomorphic maps of surfaces (see [McD–Sal]). And, one is also tempted to look at general 2-polyhedra rather than surfaces.

**Corollary (Pointed out to me by S. Ivanov):** *Let  $Y'$  be the Hausdorff limit of surfaces  $X'_\varepsilon$  of genus  $g$  with boundaries. Then,  $\dim(Y') \leq 2$ .*

In fact, such  $Y'$  topologically embeds into the  $Y$  above, since every surface  $X'$  can be isometrically embedded into a closed surface  $X$  by filling each boundary component with a spherical cap.



Notice (also following S. Ivanov) that every *planar graph* appears in the limit of surfaces of genus zero, and so the Hausdorff limits of planar graphs embed into the bubble spaces above (of genus zero).

**3.33. Approximating compact metric spaces by Riemannian manifolds.** If  $n \geq 3$ , then there is little correlation between the topology of approximating spaces  $X_\varepsilon^n$  and the limit space  $X$ . In particular, if  $X$  is a compact, connected ANR, e.g., a finite polyhedron, then one has the:

**Ferry–Okun Approximation Theorem.** *Let  $X_0$  be a compact, smooth manifold of dimension  $> 3$ . Then  $X_0$  admits a family of Riemannian metrics  $g_\varepsilon$ , such that  $(X_0, g_\varepsilon) \xrightarrow{\text{Hau}} (X, d)$  for a given path metric  $d$  on  $X$ , if and only if there is a continuous map  $X_0 \rightarrow X$  surjective on the fundamental groups.*

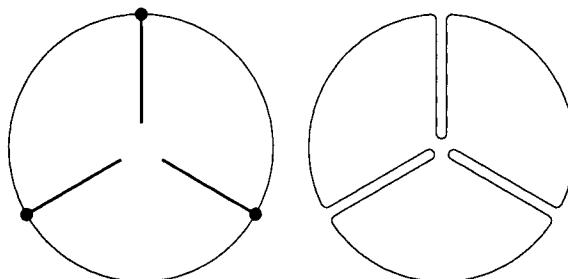
**Remarks:** (a) The “only if” part is trivial, see 3.31.

(b) According to Bing’s theorem cited in 1.26<sub>+</sub>, every compact, connected ANR admits a path metric since every compact ANR is locally contractible and vice versa.

(c) One does not truly need  $X$  to be an ANR, but just the existence of a continuous map  $f : X_0 \rightarrow X$ , where  $f^{-1}(x) \subset X_0$  is connected for all  $x \in X$ . Such a map is known to exist under our assumptions (see [Fer]<sub>UV\*</sub>), and starting from such an  $f$ , the construction of  $g_\varepsilon$  is not hard (see [Fer–Ok]<sub>ATM</sub>).

**Examples:** (a) Let  $X$  be a closed  $n$ -dimensional manifold admitting a closed subset  $Y$  of codimension  $\geq 2$ , such that the complement is homeomorphic to  $\mathbb{R}^n$ . (This is equivalent to  $\pi_1(X) = 0$  by Morse–Smale theory for  $n \geq 5$  and by Freedman’s theorem for  $n = 4$ , while the case  $n = 3$  amounts to the Poincaré conjecture.) Then  $X$  can be approximated by  $n$ -balls with path metrics, which is especially clear if  $X$  is a Riemannian manifold and  $Y$  is a piecewise smooth subpolyhedron. In this case, we consider small  $\varepsilon$ -neighborhoods  $U_\varepsilon(Y)$  and observe that the complements  $X_\varepsilon = X \setminus U_\varepsilon(Y)$  with induced *path* metrics Hausdorff-converge to  $X$ . (This fails to be true for, say, hypersurfaces  $Y$  in  $X$  since the complement is disconnected near the points  $y \in Y$ .)

(b) Take the  $n$ -ball  $B^n$  with some triangulation, take the cone from the center over the  $k$ -skeleton and cut away a small ball around the center. Then move the boundary sphere inside  $B$  along the resulting  $(k+1)$ -dimensional protrusion.



If  $n - 2 > k \geq 1$ , then the induced Riemannian (i.e., path) metric on the protruded (or rather intruded) sphere is close to the induced metric, and for a sufficiently fine triangulation we get a reasonable approximation of

$B^n$  by  $(S^{n-1}, g_\varepsilon)$ . This is easy to adjust to an actual convergence  $(S^{n-1}, g'_\varepsilon) \rightarrow B^n$ , which allows the Hausdorff approximation of  $n$ -balls by  $(n-1)$ -spheres for  $n \geq 4$ . Since  $n$ -spheres can be approximated by  $n$ -balls for  $n \geq 2$  (just look at  $S^n \setminus \{0\}$ ), we see with (a) that every compact, simply connected manifold  $X$  can be Hausdorff-approximated by  $n$ -spheres for each  $n \geq 3$ . (Notice that we excluded the Poincaré 3-spheres  $\Sigma$  in (a), but these can be approximated by  $\Sigma \times \varepsilon S^2$  for  $\varepsilon \rightarrow 0$  and (a) does apply to  $\Sigma \times S^2$  by Smale's theorem.)

**3.34. On the regularity of approximation.** Notice that the approximation in (a) above is by far more regular than in (b). In fact, one can use the construction of (a) in order to achieve the following

**Regular Approximation.** *Let  $X$  be a closed, simply connected manifold of dimension  $\geq 5$  with a piecewise Euclidean path metric. Then  $X$  can be Hausdorff-approximated by piecewise Euclidean  $n$ -balls  $X_\varepsilon$  with  $\text{geo}(X_\varepsilon) \leq \text{const} = \text{const}(X)$ .*

(The proof is straightforward and is left to the reader).

**Remarks:** The approximation above works with  $(n+1)$ -spheres instead of  $n$ -balls, since  $B^n = S^{n+1}/S^1$ . But, it is impossible with  $n$ -spheres  $X_\varepsilon$  if  $X$  is nonhomeomorphic to  $S^n$ , since the maps  $\varphi: X_\varepsilon \rightarrow X$  will have rather disconnected preimages as  $\deg(\varphi_\varepsilon) \neq 1$  in the above sense.

**Conjecture:** The regular approximation  $X_\varepsilon \xrightarrow{\text{Hau}} X$  with all  $X_\varepsilon$  homeomorphic to a fixed  $X_0$  is possible whenever  $\dim X_0 > \dim X$  and there is a map  $X_0 \rightarrow X$  surjective on  $\pi_1$ . Furthermore, if  $\dim X_0 = \dim X$ , one probably only needs a map  $X_0 \rightarrow X$  of degree one for such an approximation.

**Question:** Is it possible to define some regularity in purely topological terms, e.g., by requiring the spaces  $X_\varepsilon$ , or even better  $\lambda X_\varepsilon$  for  $\lambda \geq 1$ , to have a uniform bound on their local topology? Some steps in this direction are indicated in 3.35 below.

**3.34 $\frac{1}{2+}$ . Regular convergence in  $\mathbb{R}^n$ .** Our guiding example is given by semialgebraic subsets  $X_\varepsilon \subset \mathbb{R}^n$  of degrees bounded by a constant as they Hausdorff-converge to some  $X \subset \mathbb{R}^n$ . This limit is again a semialgebraic subset with  $\deg(X) \leq \sup \deg(X_i)$ . We want to extend this picture to more general closed subsets  $X$  in  $\mathbb{R}^n$ , i.e., to define some measure of complexity, or a sequence of such measures, such that the complexity of every compact,  $C^\infty$ -smooth submanifold is *finite*, and then we would study the Hausdorff limits  $X_\varepsilon \rightarrow X$ , where the complexities of  $X_\varepsilon$  are bounded by a fixed

constant. We would like such limits  $X$  to be as similar as possible to diffeomorphic images of semialgebraic sets. Here is a possible candidate for such complexity.

**Definition of  $\text{vol}^{(r)}(X)$ .** Consider a smooth,  $n$ -dimensional submanifold  $X$  in a smooth manifold  $Y$  and let  $Y' = \text{Gr}_n(Y)$  denote the space of the tangent  $n$ -planes in  $Y$ . The submanifold  $X$  naturally lifts to  $Y'$ , then to  $Y'' = \text{Gr}_n(Y')$ , to  $Y''' = \text{Gr}_n(Y'')$ , etc., and the  $i$ -th lift is denoted by  $X^{(r)} \subset Y^r$ . We apply this construction to  $Y = \mathbb{R}^N$ , where all  $Y^r$  carry natural Riemannian metrics and set

$$\text{vol}^{(r)}(X) = \text{vol}_n X^{(r)}.$$

(One can think of  $\text{vol}^{(r)}$  as a geometric counterpart of Sobolev's norm  $\|\partial^r f\|_{L^1}$  on functions  $f$ .)

**Observation:** If  $X \subset \mathbb{R}^N$  is semialgebraic, then

$$\text{vol}^{(r)}(X) \leq \text{const} = \text{const}(r, N, \deg(X), \text{diam}(X)).$$

In fact, intersect  $X$  with a generic  $(N-n)$ -plane  $P \subset \mathbb{R}^N$  and notice that  $\text{card}(P \cap X) \leq \deg(X)$  by Bezout's theorem. Then by the Buffon–Crofton formula, we evaluate  $\text{vol}^{(1)} = \text{vol}_n(X)$  by

$$\text{vol}_n(X) = \int \text{card}(P \cap X) dP \leq c_N(\text{diam}(X))^n \deg(X).$$

This equally applies to all  $X^{(t)}$  and yields our inequality (where the reader is welcome to furnish the details).

**Problem:** Study the geometry of compact subsets  $X \subset \mathbb{R}^N$  which are Hausdorff limits of smooth  $n$ -dimensional submanifolds  $X_\varepsilon$  with  $\text{vol}^{(r)}(X_\varepsilon) \leq \text{const}$ , for  $r = 1, 2, \dots$ .

**Exercise:** Show that if such a limit for  $n = 1$  is a piecewise smooth curve in  $\mathbb{R}^N$ , then the number of breaks of the  $k$ -th derivative of  $X$  is controlled by  $\text{vol}^{k+2}$ .

**Remark:** The above probably generalizes to piecewise smooth  $X \subset \mathbb{R}^N$  with  $\dim X \geq 2$ . But more complicated singularities are not necessarily reflected in  $\text{vol}^{(r)}(X)$ , not even for  $\dim X = 1$ , as was recently pointed out to me by Joseph Fu. For example, the graph  $X \subset \mathbb{R}^2$  of the function  $y = x^{(k+1)/k}$ ,  $k = 1, 2, \dots$  becomes nonsingular as we pass to  $X^{(r)}$  with  $r \geq 1$ . Then, following Fu, one easily makes a  $C^1$ -curve  $X$  in the unit disk with infinitely many  $C^2$ -singularities, where all  $X^{(r)}$  are  $C^\infty$ -smooth for  $r \geq 1$ :

take the graph of  $f(x) = \int \varphi(x) dx$ , where the graph of  $\varphi$  is  $C^\infty$ -smooth with  $\varphi'(x) = \infty$  at infinitely many values of  $x$ .

**Questions:** How much does the condition  $\text{vol}^{(r)} X_\varepsilon \leq \text{const}_r < \infty$  control the singularities of  $X = \lim_{\varepsilon \rightarrow \infty} X_\varepsilon$ ? What should one add to  $\text{vol}^{(r)} < \infty$  to make  $X$  stratifiable? Which global (topological and geometric) invariants of smooth (and more generally, stratified)  $X$  can be bounded in terms of  $\text{vol}^{(r)} X$ ,  $r = 1, 2, \dots$ ? (See [Fu]CMCC and [Fu]MAF for the case  $r = 1$ .) What is the effect of  $\text{vol}^{(r)}(X)$  (and other geometric complexities for that matter) on the rate of Hausdorff-approximation of  $X$  by semialgebraic subsets  $Y$ ? Here we seek  $Y = Y_\varepsilon$  of minimal possible degree  $\deg_\varepsilon = \deg Y_\varepsilon$  such that  $\text{dist}_H(X, Y_\varepsilon) \leq \varepsilon$  and study the asymptotic behavior of  $\deg_\varepsilon$  for  $\varepsilon \rightarrow 0$ . Also, we can look at  $\text{dist}_H(X^{(r)}, Y_\varepsilon^{(r)})$  for  $r \geq 2$ .

**Intrinsic vol<sup>(r)</sup>.** Now let  $X$  be a Riemannian manifold and try to define some  $\text{vol}^r(X)$  in Riemannian terms. One possibility is to look at all path isometric embeddings  $X \rightarrow \mathbb{R}^N$  for large  $N$  and minimize  $\text{vol}^{(r)}$  for the images of these embeddings. (Or, one may use some canonical embedding of  $X$  into an  $L_2$ -space of functions or tensors on  $X$ .) Similarly, one may define  $\text{dist}_H^{(r)}(X, Y)$  via path-isometric embeddings  $X, Y \rightarrow \mathbb{R}^N$ .

Alternatively, one may look at the integrals of suitable expressions in the curvature tensor and its derivatives. Here one must keep an eye on the picture of  $X = X_0 \times S_\varepsilon^1$ , where  $X_0$  is a badly curved manifold and  $S_\varepsilon^1$  is a very short circle. We want the curvature of  $X_0$  to be felt by our integrals over  $X$  no matter how small  $\varepsilon$  can be. This can be achieved by normalizing such integrals with  $(\text{vol}(X))^{-\alpha}$  or  $(\text{InjRad})^{-\beta}$ , or with something else of this kind.

Another possibility is to look at the manifold  $X'$  of orthonormal frames in  $X$  with the metric naturally defined with the Levi-Civita connection in  $X$ . Then one defines  $X^{[2]} = (X')', \dots, X^{[r]} = (X^{[r-1]})'$  and measures the  $r$ -th complexity of  $X$  by the Hausdorff distance from  $X^{[r]}$  to the cartesian product of  $X$  by the fiber of the fibration  $X^{[r]} \rightarrow X$  (or something else in this spirit).

Ultimately, we can measure the complexity of  $X$  by the minimal number  $d = d_\varepsilon(X)$  of “ $\varepsilon$ -standard pieces” into which one can decompose  $X$ . Here, one has to specify what “ $\varepsilon$ -standard” means. For example, one might declare the convex simplices in  $\mathbb{R}^n$  to be “standard,” so that “ $\varepsilon$ -standard” would then mean “being within Lipschitz distance  $\leq \varepsilon$  from something standard.” (Being more generous, one may also regard simplices like  $\{x, y : 0 \leq x \leq 1, 0 \leq y \leq x^\alpha\}$  as “standard” (compare [Gro]SGSS).)

**Concluding remark.** To bring the discussion back to solid ground, one

has to:

- (a) analyse the relation between different notions of complexity.
- (b) evaluate the complexity for concrete examples, e.g., decide when  $\text{vol}^{(r)}$  of the smooth locus of a minimal variety in  $\mathbb{R}^N$  is finite; pose and solve similar problems for Einstein manifolds and their singular limits.

We hope that the reader finds the perspective attractive. A step in a somewhat different direction is indicated below.

**3.35. Hausdorff convergence and collapse.** There are several definitions expressing the idea that a family  $X_\varepsilon$  of  $n$ -dimensional spaces collapses, for  $\varepsilon \rightarrow 0$ , to something of dimension  $< n$ .

(1) *Uryson width and collapse.* Define  $\text{wid}_k(X)$ , also denoted  $\text{diam}_k(X)$ , as the infimum of the numbers  $\delta$  such that  $X$  admits a continuous map into a  $k$ -dimensional polyhedron, say  $f: X \rightarrow P$ , such that

$$\text{diam } f^{-1}(p) \leq \delta$$

for all  $p \in P$ . Then the convergence  $\text{wid}_{n-1} X_\varepsilon \rightarrow 0$  signifies some kind of collapse, called the *Uryson collapse* of  $X_\varepsilon$ .

(2) *Kuratowski embedding and the filling radius.* Let  $X$  be a closed, oriented manifold embedded into a metric space  $Y$ . Then  $\text{FilRad}(X \subset Y)$  is defined as the infimal  $\rho$  such that  $X$  bounds in its  $\rho$ -neighborhood, i.e., the fundamental class  $[X] \in H_n(X)$  goes to zero under the inclusion  $X \hookrightarrow U_\varepsilon(X)$ . (If  $X$  is nonorientable, one makes this definition with  $\mathbb{Z}_2$ -coefficients.) Next, we observe that every compact metric space  $X$  isometrically embeds into the space  $Y$  of functions on  $X$  with the uniform norm,  $x \mapsto \text{dist}(\cdot, x) \in Y$ . Then

$$\text{FilRad}(X) \stackrel{\text{def}}{=} \text{FilRad}(X \subset Y)$$

for the Kuratowski embedding  $X \subset Y$ .

**Exercise:** Show that  $\text{FilRad}(X)$  equals the infimal  $\rho$  such that there exists a pseudomanifold  $X$  with a boundary endowed with a metric such that  $X$  is isometric to the boundary  $\partial X' \mid \text{dist}_{X'}$  and  $\text{dist}(x', \partial X') \leq \rho$  for all  $x' \in X$ .

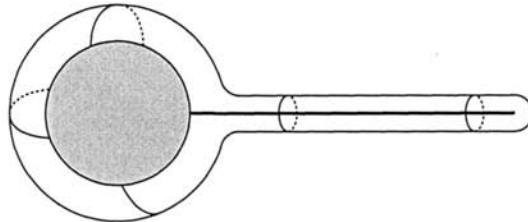
The definition of  $\text{FilRad}$  extends to manifolds  $X$  with boundaries by tracing the vanishing of  $[X] \in H_n(X, \partial X)$  as one enlarges  $X$  to  $U_\rho(X)$  and  $\partial X$  to  $U_\rho(\partial X)$  in the space of functions on  $X$  (see [Gro]FRM).

The *filling collapse* of  $X_\varepsilon$  is defined by requiring that  $\text{FilRad } X_\varepsilon \rightarrow 0$ . Since  $\text{FilRad} \leq \text{wid}_{n-1}$  (by a trivial argument, see [Gro]FRM), the Uryson collapse implies the filling collapse.

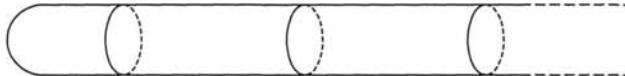
**Example:** We shall see in Ch. 8+ that if  $X_\varepsilon$  are Riemannian manifolds with bounded curvatures  $|K(X_\varepsilon)| \leq \text{const}$ , then the filling collapse is equivalent to  $\text{injRad} \rightarrow 0$  (at all points in  $X_\varepsilon$ ) which is, in turn, equivalent to Uryson's collapse. In fact, the Uryson and filling collapses are also equivalent under the one-sided bound  $K(X_\varepsilon) \geq -\text{const}$  (see [Grov-Pet], [Per]SCBB).

**Remarks:** (a) The collapse does not exclude  $\dim \lim_H X_\varepsilon \geq \dim X_\varepsilon$ . For example, we can first approximate  $S^n$  for  $n > 3$  by  $X_\varepsilon$  homeomorphic to  $S^3$  and then take collapsing(!)  $X'_\varepsilon = X_\varepsilon \times \varepsilon S^{n-3}$ , which also converge to  $S^n$ .

(b) One may have a partial collapse of  $X_\varepsilon$ , as for the boundary of the  $\varepsilon$ -neighborhood of an  $n$ -ball in  $\mathbb{R}^n$ ,  $n \geq 3$ , with a segment sticking out of it (compare (b) in 3.33 $\frac{1}{2}$ ).



**3.36. Controlled contractibility against collapse.** Let  $\rho = \rho(r) \geq r$  be a (control) function for  $0 \leq r < R$  and say that a metric space  $X$  is  $\rho$ -contractible if every subset in  $X$  inside a ball of radius  $r$  can be contracted within the concentric ball of radius  $\rho(r)$ . When this applies for  $R = \infty$  (i.e., for all  $r \geq 0$ ), this implies the uniform contractibility of  $X$ , which, for noncompact  $X$  is strictly stronger than just contractibility, no matter how fast  $\rho(r)$  may grow. Here is a contractible but not uniformly contractible  $\mathbb{R}^2$ :



**Exercise:** Show that every complete, uniformly contractible surface has infinite area (see [Gro]FRM for the case  $\dim \geq 3$ ).

In what follows, we shall be concerned with  $R < \infty$  and families  $X_\varepsilon$  of compact spaces. Such  $X_\varepsilon$  are called *controllably locally contractible* if they are  $\rho$ -contractible for a continuous function on a segment  $[0, R]$  vanishing at  $r = 0$ .

**Observation:** *A controllably locally contractible family of  $n$ -dimensional manifolds does not (filling) collapse.*

**Proof.** If  $X \subset Y$  is  $\rho$ -contractible, then every  $(n+1)$ -dimensional polyhedron lying in the  $\varepsilon$ -neighborhood  $U_\varepsilon(X) \subset Y$  for a small  $\varepsilon \leq \varepsilon_0 = \varepsilon_0(R, \rho) > 0$ , retracts onto  $X$  by a standard argument of the induction by skeletons. It follows that  $[X]$  does not vanish in  $U_\varepsilon(X)$  and so  $\text{FilRad}(X) \geq \varepsilon_0(R, \rho)$ .

**Remarks:** (a) This argument also applies to balls in  $X_\varepsilon$  and shows that  $X_\varepsilon$  nowhere collapses, i.e., no sequence of balls  $B(x_\varepsilon, r_\varepsilon) \subset X_\varepsilon$  with  $r_\varepsilon \geq r_0 > 0$  collapses.

(b) The collapse could have been as easily ruled out by *controlled local acyclicity*, which is somewhat weaker than such contractibility.

Non-collapsed convergence  $X_\varepsilon \xrightarrow{\text{Hau}} X$  imposes nontrivial restrictions on the topology of  $X$ , e.g.,  $\dim(X)$  cannot be smaller than  $n = \dim(X_\varepsilon)$ . But, the dimension may jump up quite dramatically.

*There exists a family of Riemannian manifolds  $X_\varepsilon$  which are controllably locally contractible, all diffeomorphic to  $S^5$ , and which Hausdorff converges to an infinite-dimensional space  $X$ . (See [Fer–Ok]ATM).*

The space  $X$  above is an instance of a *Dranishnikov manifold*, which looks homologically, locally and globally, like the sphere  $S^5$  but which nevertheless has infinite *Lebesgue* covering dimension.

In general, spaces  $X$  appearing in the completion of the space  $\mathcal{X}(n, \rho)$  of  $n$ -dimensional Riemannian manifolds with local contractibility control by a given  $\rho = \rho(r)$ ,  $r \in [0, R]$ , has been studied in [Fer]CSHT, [Fer]TFT and [Dra–Fer]. For example, it is shown in [Fer]TFT that if  $X_i \in \mathcal{X}(n, \rho)$  converge to some  $X$ , then for  $n \neq 3$ , there are at most finitely many mutually nonhomeomorphic manifolds among the  $X_i$ , and moreover if  $X$  is finite-dimensional, then all  $X_i$  sufficiently close to  $X$  (i.e., for  $i \geq i_0$ ) are mutually homeomorphic. (It is obvious that any two manifolds  $X_i$  and  $X_{i'}$  close to  $X$  are homotopy equivalent).

It would be interesting to extend the results above to the situation where a partial collapse is allowed, as in 3.32 for graphs and surfaces. For example, one can look at  $n$ -dimensional manifolds  $X$  which are locally  $\rho$ -contractible (or just acyclic) up to dimension  $(n-2)$ , as is the case with the surfaces (see 3.32). Here again, collapse is reflected in cut-points in the limit. Then one wishes to admit some kind of “stratified collapse” including, for example,  $X_\varepsilon \times Y \xrightarrow{\text{Hau}} X \times Y$  for the above  $X_\varepsilon \xrightarrow{\text{Hau}} X$  with possible collapse at the

cut-points in  $X$ , and, more generally, the collapse pattern as complicated as for

$$X_\varepsilon \times X'_\varepsilon \times X''_\varepsilon \times \cdots \xrightarrow{\text{Hau}} X \times X' \times X'' \times \cdots$$

In fact, one can enhance convergence by cutting away the collapsing parts of  $X_\varepsilon$ . Namely, for a given  $\delta$  and  $r$ , one removes from  $X_\varepsilon$  the  $\delta$ -collapsed balls  $B$  of radius  $r$ , where “ $\delta$ -collapsed” may mean one of the following:

1.  $\text{wid}_{n-1} B \leq \delta$ ,
2.  $\text{FilRad } B \leq \delta$ ,
3.  $B$  is not contractible in the concentric ball of radius  $\delta^{-1}r$ ,
4. something else in the same spirit.

We denote the remaining  $\delta$ -thick part of  $X_\varepsilon$  by  $X_\varepsilon(\delta, r)$ , pass to the limit as  $\varepsilon \rightarrow 0$ , send  $\delta \rightarrow 0$ , and finally let  $r \rightarrow 0$ . The resulting space  $X^{\text{thick}}$  coincides with  $X = \lim_{\text{H}} X_\varepsilon$  in the noncollapsed case, and it may exist in the cases where the original family  $X_\varepsilon$  admits no Hausdorff convergent subsequence. The most satisfactory picture arises if one can find a thick part  $X'_\varepsilon(\delta, r)$  of  $X$  with boundary  $\partial X'_\varepsilon(\delta, r)$  having  $\text{wid}_{n-r} \rightarrow 0$  for  $\varepsilon, \delta \rightarrow 0$ , while the interior of  $X'_\varepsilon(\delta, r)$  has controlled local contractibility  $r$ -far from the boundary (as happened in 3.35 (b)). The question which remains open is that of finding reasonable local conditions which would imply such behavior.

Now, following the ideas of geometric measure theory, we indicate in the following sections another way to cut away undesirable thin parts of  $X_\varepsilon$ .

# Chapter $3\frac{1}{2}_+$

## Convergence and Concentration of Metrics and Measures

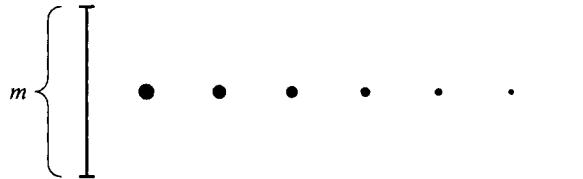
### A. A review of measures and mm spaces

**3 $\frac{1}{2}$ .1.** When we speak of measures  $\mu$  on a metric space  $X$ , we always assume that  $X$  is a *Polish space*, i.e., *complete with a countable base*, and that “measure” means a *Borel measure*, where all Borel subsets in  $X$  are measurable. We are mostly concerned with *finite measures* where  $X$  has *finite (total) mass*  $\mu(X) < \infty$ , but we also allow  $\sigma$ -finite *measure spaces*  $X$ , which are the countable unions of  $X_i$  with  $\mu(X_i) < \infty$ . For example, the ordinary  $n$  dimensional Hausdorff measure in  $\mathbb{R}^n$  is  $\sigma$ -finite, while the  $k$ -dimensional Hausdorff measure on  $\mathbb{R}^n$  for  $k < n$  is not  $\sigma$ -finite. But, we may restrict such a measure to a  $k$ -dimensional submanifold  $V \subset \mathbb{R}^n$ , i.e., we declare  $\mu_k(U) = \mu_k(U \cap V)$  for all open  $U \subset \mathbb{R}^n$ , in which case the measure becomes  $\sigma$ -finite and admissible in our discussion.

Polish metric spaces with  $\sigma$ -finite measures, denoted  $X = (X, \text{dist}, \mu)$  are called *mm spaces*.

**Reversed definition of mm spaces:** One could start with an abstract measure space  $(X, \mu)$  and then introduce a metric as a measurable function  $d$  on  $X \times X$  satisfying the metric axioms. If  $\mu$  appears as a Borel measure on a Polish space, as we will always assume to be the case, then  $(X, \mu)$  is a *Lebesgue (Rochlin) space*, i.e., it is measure-isomorphic to a real segment of length  $m \leq \infty$  with a finite or countable collection of *atoms*, i.e., points  $x_i$  with positive measures (masses)  $m_i = \mu(x_i)$ . Here is a picture of such a

space with atoms ordered according to their mass.



If, for example, we restrict ourselves to measures of *mass one without atoms*, then all mm spaces are representable by measurable functions  $d$  on the square  $[0, 1]^2$ .

Notice that every finite measure  $\mu$  can be *normalized* to mass one by setting  $\nu(U) = \mu(U)/\mu(X)$  for all  $U \subset X$ . Such normalized measures are often called *probability measures*, and  $\nu(U)$  is interpreted as the probability of the event  $x \in U$ .

Our basic example is a Riemannian manifold  $V$  of dimension  $n$  with  $n$ -dimensional Riemannian volume (measure)  $\text{vol}_n$ . This can be defined as the  $n$ -dimensional Hausdorff measure (using countable coverings by balls) or axiomatically by observing that  $\text{vol}_n$  is uniquely characterized by the following two properties:

1. *Monotonicity.* If  $V_1$  admits a bijective 1-Lipschitz map onto  $V_2$ , then  $\text{vol}_n(V_1) \geq \text{vol}_n(V_2)$ .
2. *Normalization.* The Euclidean cube  $[0, 1]^n$  has  $\text{vol}_n([0, 1]^n) = 1$ .

We are also interested in non-Riemannian measures, such as the *Gaussian* measure on  $\mathbb{R}^n$  given by  $d\mu = e^{-\|x\|^2} dx_1 dx_2 \cdots dx_n$  confronted with the *ordinary Euclidean metric* on  $\mathbb{R}^n$ .

*Pushforward measures.* A continuous (or just Borel measurable) map  $f : X \rightarrow Y$  pushes forward measures  $\mu$  from  $X$  to  $\mu_* = f_*(\mu)$  on  $Y$  by  $\mu_*(U) = \mu(f^{-1}(U))$  for all  $U \subset Y$ .

Notice that the pushforward of a Riemannian measure is, typically, non-Riemannian, even if the map in question is quite regular. For example, if  $f : V_1 \rightarrow V_2$  is a *smooth* map between equidimensional manifolds, then  $f_*(\text{vol}_n)$  is rarely Riemannian. For example, if  $V_1$  is a closed manifold, then  $f_*(\text{vol}_n)$  is not Riemannian unless  $f$  is a covering map. On the other hand, there are quite a few (nonsmooth!) Lipschitz maps pushing forward Riemannian measures to Riemannian measures (see Exercise 3½.16).

**Examples (Archimedes).** (a) The normal projection of the unit sphere

$\mathbb{R}^{n+1} \supset S^n \rightarrow \mathbb{R}^{n-1} \subset \mathbb{R}^{n+1}$  pushes forward the spherical measure to  $2\pi \cdot$ (Lebesgue measure) on the unit ball in  $\mathbb{R}^{n-1}$ .

(b) The “squaring map” from the sphere  $S^{2n+1} \subset \mathbb{C}^{n+1}$  to the unit simplex  $\Delta^n \subset \mathbb{R}_+^{n+1}$  given by

$$(z_0, \dots, z_n) \mapsto (|z_0|^2, \dots, |z_n|^2),$$

which is an instance of a *moment map*, sends the spherical measure to  $(2\pi)^n \cdot$ (Lebesgue measure) on  $\Delta^n$ .

(c) The normal projection of the unit ball  $B^{n+1} \subset \mathbb{R}^{n+1}$  to  $\mathbb{R}$  pushes forward the Lebesgue measure on  $B^n$  to  $(\sqrt{1-x^2})^n dx$  on  $[-1, 1] \subset \mathbb{R}$ .

We present below some standard facts about measures and mm spaces, where the routine proofs are left to the reader (who may also consult [Parth]).

**The metric  $\text{me}_\lambda$  on maps  $X \rightarrow Y$ .** Here,  $(X, \mu)$  is a measure space and  $(Y, \text{dist})$  is a metric space. Given maps  $f, g: X \rightarrow Y$ , we define  $\text{me}_\lambda(f, g)$  for  $\lambda \geq 0$  as the *minimal* or, better, *infimal* number  $\varepsilon > 0$  such that  $f$  and  $g$  are  $\varepsilon$  close in  $Y$  away from a subset of measure  $\lambda\varepsilon$  in  $X$ ,

$$\mu\{x \in X : \text{dist}(f(x), g(x)) \geq \varepsilon\} \leq \lambda\varepsilon.$$

The metrics  $\text{me}_\lambda$  for different  $\lambda > 0$  are (obviously) mutually bi-Lipschitz equivalent. Thus, the notion of  $\text{di}_\lambda$ -convergence is independent of  $\lambda > 0$  and is customarily referred to as *convergence in measure*. Observe that  $\text{me}_\lambda$  is not, strictly speaking, a metric, since it can become infinite when  $\mu(X) = \infty$  or, for finite  $\mu(X)$  if  $\lambda = 0$ . But everything we say about  $\text{me}_\lambda$  still makes sense in these cases if we restrict our attention to maps  $f: X \rightarrow Y$  which lie within a finite distance from a fixed  $f_0: X \rightarrow Y$ .

Notice that the metric  $\text{me}_0$  is quite different from the rest of the  $\text{me}_\lambda$ . It is called the *sup-metric* or  $L_\infty$  metric on maps:

$$\text{me}_0 = \sup_{x \in X} \text{dist}(f(x), g(x)).$$

**An apology:** There is something artificial in the way we make the metric out of  $\varepsilon$  and  $\lambda\varepsilon$ . It would be more logical to use both numbers independently, say  $\varepsilon$  and  $\kappa$  (instead of  $\lambda\varepsilon$ ) and say: “ $f$  and  $g$  are  $(\varepsilon, \kappa)$  close if  $\mu\{x \in X : \text{dist}(f(x), g(x)) \geq \varepsilon\} \leq \kappa$ .” To make this consistent, we need a generalized notion of metric space, where the distance is measured by a pair of numbers, or rather by a subset in  $\mathbb{R}^2$ . Ultimately, the metric should be replaced by a certain partial order on  $X \times X$ , but the self limitations of the present exposition force us into a procrustean bed of metric spaces.

**(1) Exercises:** (a) Show that if  $Y$  is a *complete* metric space, then so is the space of maps  $X \rightarrow Y$  with the metric  $\text{me}_\lambda$  for  $\lambda \geq 0$ . Furthermore, if  $Y$  is Polish, then the space of maps is also Polish for  $\text{me}_\lambda$  if  $\lambda > 0$ .

(b) Recall that the  $L_p$ -metric between  $f$  and  $g$  is defined for  $1 \leq p < \infty$  by

$$\text{dist}_{L_p}(f, g) = \left( \int_X (\text{dist}(f(x), g(x))^p d\mu \right)^{1/p},$$

and observe that  $\text{me}_\lambda$  for  $\lambda > 0$  can be bounded by  $\text{dist}_{L_p}$  via the famous (and obvious) *Chebyshev inequality*

$$\int_X (\text{dist}(f, g))^p d\mu \geq \varepsilon^p \mu\{x \in X : \text{dist}(f(x), g(x)) \geq \varepsilon\}$$

for all  $\varepsilon > 0$  and  $p > 0$ .

(c) Let  $d: X \times X \rightarrow \mathbb{R}_+$  be a symmetric measurable function satisfying the triangle inequality. Invoke the Kuratowski map from  $X$  to the space  $L_\infty(X)$  of functions  $X \rightarrow \mathbb{R}$  with the  $L_\infty$  metric  $K: X \rightarrow L_\infty(X)$  for  $K: x \mapsto d_x(y) = \text{dist}(x, y)$ . Denote by  $\mu_*$  the pushforward of the measure  $\mu$  from  $X$  to  $L_\infty(X)$ . Recall that  $\mu$  is (assumed) Lebesgue and show that the  $L_\infty$ -closure of the image  $K(X) \subset L_\infty(X)$  has countable base. Thus, this closure  $(Cl(K(X)), \mu_*, \text{dist}_{L_\infty})$  is an mm-space in our sense. Furthermore, if  $d$  does not vanish away from the diagonal in  $X \times X$ , then  $K$  is injective (as well as isometric for  $d \leftrightarrow \text{dist}_{L_\infty}$ ), and so  $CL(K(X))$  equals the completion of  $X$  with respect to  $d$ .

**3<sub>2</sub><sup>1</sup>.2. The metric  $\square_\lambda$  on maps**  $d: X \times X \rightarrow Y$ . One could use  $\text{me}_\lambda$  for  $(X \times X, \mu \times \mu)$ , but there is another metric, denoted  $\square_\lambda(d, d')$  which is defined as the supremal  $\varepsilon$  such that  $d$  and  $d'$  are  $\varepsilon$ -close in  $Y$  outside a subset  $X_\varepsilon \subset X$  of measure  $\leq \lambda\varepsilon$ , i.e.,

$$\text{dist}(d(x_1, x_2), d'(x_1, x_2)) \leq \varepsilon$$

for  $(x_1, x_2) \in (X \setminus X_\varepsilon) \times (X \setminus X_\varepsilon)$ . Clearly  $\square_\lambda \geq \text{me}_\lambda$ .

In what follows, we will be concerned with  $\square_\lambda$  on the space  $D$  of symmetric functions  $d: X \times X \rightarrow \mathbb{R}$  satisfying the triangle inequality.  $\square_\lambda$

**Exercise:** Show that  $(D, \square_\lambda)$  is a Polish path metric space for all  $\lambda > 0$ .

## B. $\square_\lambda$ -convergence of mm-spaces

**3<sub>2</sub><sup>1</sup>.3.** Every Lebesgue space  $(X, \mu)$  can be *parametrized* by the segment  $[0, m]$  for  $m = \mu(X)$ , where the parametrization refers to a *measure-preserving* map  $\varphi: [0, m] \rightarrow X$  (which is necessarily surjective up to

measure zero) and where “measure preserving” means  $\varphi_*(\nu) = \mu$  for the Lebesgue measure  $\nu$  on  $[0, m)$ . Notice that such a  $\varphi$  is by no means unique, and it can be chosen to be bijective if  $X$  contains no atoms.

If  $X$  comes along with a metric as well as  $\mu$ , one can pullback this metric  $\text{dist}: X \times X \rightarrow \mathbb{R}$  to a function  $d$  on  $[0, m)^2$  that is given by

$$d(t, t') = \text{dist}(\varphi(t), \varphi(t')).$$

**Definition of  $\square_\lambda$ .** Let  $X$  and  $X'$  be two mm-spaces of equal mass. Parametrize  $X$  and  $X'$  by  $[0, m)$ , pullback the metrics  $\text{dist}$  on  $X$  and  $\text{dist}'$  on  $X'$  to functions  $d$  and  $d'$  on  $[0, m)^2$ , and set

$$\underline{\square}_\lambda(X, X') = \inf \square_\lambda(d, d'),$$

where the infimum is taken over all parametrizations  $\varphi$  and  $\varphi'$  of  $X$  and  $X'$  by  $[0, m)$ .

**The case  $m \neq m'$ .** If  $X$  and  $X'$  have unequal masses  $m = \mu(X)$  and  $m' = \mu(X')$ , then there are several possibilities for defining the distance  $\underline{\square}_\lambda(X, X')$ . First of all, we set  $\underline{\square}_\lambda(X, X') = \infty$  if  $m < \infty$  while  $m' = \infty$ , so we are left with the case where both masses  $m$  and  $m'$  are finite. Here, we must agree on what is the distance between  $(X, \mu, \text{dist})$  and  $(X, r\mu, \text{dist})$  for a given  $r > 0$ . It could be  $|\log(r)|$ , but we will stick to  $|r - 1|\mu(X)$ . Then we define  $\underline{\square}_\lambda(X, X')$  for  $m < m'$  as the maximal metric compatible with this convention. This is equivalent (by an easy argument) to

$$\underline{\square}_\lambda(X, X') = m' - m + \underline{\square}_\lambda(X, X'_m),$$

where  $X'_m = (X', (m/m')\mu', \text{dist}')$ , provided  $m' \geq m$ . (If we had used the  $|\log|$  alternative, we would set

$$\underline{\square}_\lambda(X, X') = |\log(r)| + \underline{\square}_\lambda(X_1, X'_1),$$

where the subscript “1” signifies the normalization of the measure  $\mu \sim (1/m)\mu$ .)

Later on (see 3½.7), we shall see that  $\underline{\square}_\lambda$  is indeed a metric on the *isomorphism classes* of mm-spaces of finite mass, where we use the following

**Definition of  $\text{Supp } \mu$  and of mm-isomorphisms.** The *support* of a measure  $\mu$  on a metric space  $X$  is the *minimal closed* subset  $Y \subset X$  such that  $\mu(X \setminus Y) = 0$ . Two mm-spaces  $X$  and  $X'$  are called *mm-isomorphic* if there exists an isometry between the supports of their respective measures, say  $\text{Supp } \mu \leftrightarrow \text{Supp } \mu'$ , such that  $\mu$  goes to  $\mu'$  under this isometry. Thus, every  $(X, \mu, \text{dist})$  is isomorphic to  $(\text{Supp } \mu, \text{dist})$ , and so dealing with  $\underline{\square}_\lambda$

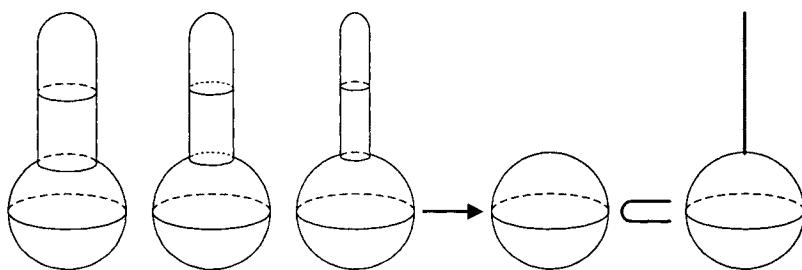
and with isomorphisms between mm spaces in general, we assume that the measures  $\mu = \mu_X$  in question have  $\text{Supp } \mu = X$ .

$\square_\lambda$ -convergence. We say that a sequence  $X_i$  of mm-spaces  $\square_\lambda$ -converges to  $X = (X, \mu, \text{dist})$  if

$$\square_\lambda(X, X_i) \rightarrow 0$$

as  $i \rightarrow \infty$ . Notice that this definition implies that  $X$  and almost all  $X_i$  have simultaneously finite or infinite masses and  $m_i = \mu(X_i) \rightarrow m = \mu(X)$ . In what follows, we will mainly be concerned with the case of mm-spaces of finite mass, while the case of infinite measure could be treated in the spirit of our approach to the Hausdorff convergence of noncompact spaces.

**Example:** Consider a sequence of spheres with thin fingers sticking out with areas going to zero.



For each  $\lambda > 0$ , the  $\square_\lambda$ -limit equals the original sphere, while the Hausdorff limit contains a straight segment as a remnant of the fingers. Also, if  $\lambda = 0$ , then there is no limit at all.

**Exercises:** (a) Let a sequence of compact metric spaces  $X_i$  Hausdorff-converge to a compact space  $X$ . Show that for every sequence of measures  $\mu_i$  on  $X_i$  with  $\mu_i(X_i) \leq m < \infty$ , there exists a subsequence  $(X_{i_j}, \mu_{i_j}, \text{dist}_{i_j})$  which  $\square_1$ -converges to  $X$  with some measure  $\mu$  on it. Moreover, if there is a function  $\kappa(\rho) > 0$ ,  $\rho > 0$ , such that the  $\rho$ -balls in all  $X_i$  have  $\mu_i(B(\rho)) \geq \kappa(\rho)$ , then the  $\mu$  above has  $\text{Supp } \mu = X$ , and  $(X_{i_j}, \mu_{i_j}, \text{dist}_{i_j})$  converge to  $(X, \mu, \text{dist})$  with respect to the metric  $\square_0$ .

(b) Let  $X = (X, \text{dist}, \mu)$  be an arbitrary mm space of finite mass  $m = \mu(X)$ . Show that  $\varepsilon X = (X, \varepsilon \text{dist}, \mu)$   $\square_1$ -converges to a one-point space of mass  $m$  as  $\varepsilon \rightarrow 0$ . This can also happen for  $m = \infty$  if we allow atoms of infinite mass in the limit. But typically, there is no shade of convergence of  $\varepsilon X$  to an atom for spaces of infinite mass; just consider  $X = \mathbb{R}^n$  for instance.

(c) Study the convergence  $X_i \rightarrow X$  where all spaces in question consist of at most  $N$  atoms. Notice that in the limit, the number of atoms may drop down for two reasons: either some atoms collide, or some disappear as their mass goes to zero.

(d) Let  $x_1, x_2, \dots$  be a *uniformly distributed sequence* of points in an mm space  $X$ , that is,

$$\frac{1}{N} \sum_{i=1}^N f(x_i) \rightarrow \int_X f d\mu$$

for every bounded Lipschitz function  $f$  on  $X$ . Show that the finite spaces

$$(\{x_1, x_2, \dots, x_N\}, \text{dist}_X, \mu_N(x_i) = N^{-1}\mu(X))$$

converge to  $X$  in the  $\square_1$ -metric, provided that  $\mu(X) < \infty$ .

(e) Let  $S^n$  be the unit sphere with the normalized  $O(n+1)$ -invariant measure. Show that  $\square_1(S^n, S^{n-1}) \rightarrow 0$  as  $n \rightarrow \infty$ , although the sequence of these spheres  $\square_1$ -diverges as  $n \rightarrow \infty$ .

(f) Let  $X$  be a Riemannian manifold with a probability measure, say  $X = (X, \text{dist}, \mu)$ , and let  $\lambda_1 \geq \lambda_2 \geq \dots$  be a sequence of positive numbers. Consider  $\lambda_i X = (X, \lambda_i \text{dist}, \mu)$  and take the cartesian product

$$X_n = (\lambda_1 X) \times \dots \times (\lambda_n X),$$

where we recall that the distance on  $X_n$  is

$$\text{dist}_n((x_1, \dots, x_n), (y_1, \dots, y_n)) = \left( \sum_{i=1}^n (\lambda_i \text{dist}(x_i, y_i))^2 \right)^{1/2}$$

and  $\mu_n = \mu \times \mu \times \dots \times \mu$ . Show that the sequence  $X_n$   $\square_1$ -converges to some mm space  $Y$  if the series  $\sum_{i=1}^{\infty} \lambda_i^2$  converges.<sup>1</sup> Conversely, if the  $X_n$  converge, then either  $\sum_{i=1}^{\infty} \lambda_i^2 < \infty$  or  $\text{diam}(\text{Supp } \mu) = 0$  (i.e.,  $\mu$  is Dirac's  $\delta$ ). Show that if  $X = (X, \text{dist})$  is isometric to  $\mathbb{R}^n$  and  $\text{Supp } \mu = \mathbb{R}^n$ , then  $Y = (Y, \text{dist}_{\infty})$  is isometric to a Hilbert space. Study specifically the case where (i)  $\mu$  is the Gaussian measure on  $\mathbb{R}$ , i.e.,  $\mu = e^{-\pi x^2} dx$ ; (ii)  $X$  is a complete (possibly noncompact) Riemann surface of constant negative curvature of finite area and  $\mu$  is the normalized Riemannian volume (area). (iii)  $X$  is the Heisenberg group with a left-invariant metric and some  $\mu$  having  $\text{Supp } \mu = X$ .

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<sup>1</sup>This is false in general as Yann Ollivier pointed out to me. One needs a decay condition for  $\mu$  on noncompact  $X$ .

(f') Generalize the above to cartesian products of arbitrary mm spaces. Also consider the case where  $\text{dist}_n$  is defined as  $(\sum_{i=1}^n \text{dist}_i^p)^{1/p}$  for an arbitrary  $p \geq 1$ .

**Encouragement:** If the reader finds these exercises difficult, we suggest plodding on through the subsequent sections, where all the problems are eventually solved.

**3<sub>2</sub>.4. Identification of  $X$  by the measures  $\underline{\mu}_r^X$ .** We recall that the *distance matrix* map from  $\underbrace{X \times X \times \cdots \times X}_r \rightarrow M_r$  which assigns to each  $r$ -tuple of points the matrix of their mutual distances in  $X$ , and we denote by  $\underline{\mu}_r = \underline{\mu}_r^X$  the pushforward of the measure  $\mu \times \mu \times \cdots \mu$  to the space  $M_r$  of positive, symmetric  $(r \times r)$ -matrices. Notice that  $\text{Supp } \underline{\mu}_r \subset M_r$  equals our old friend  $K_r(X) \subset M_r$ , provided that  $\text{Supp } \mu = X$  (compare 1.19<sub>+</sub>).

We have already seen that the “curvature” sets  $K_r(X)$ , for  $r = 1, 2, \dots$  give a full set of invariants for compact metric spaces  $X$ . Similarly, we have the following

**3<sub>2</sub>.5. mm-Reconstruction theorem.** *If two mm-spaces  $X$  and  $X'$  with finite measures have  $\underline{\mu}_r^X = \underline{\mu}_r^{X'}$  for all  $r = 1, 2, \dots$ , then  $X$  is isomorphic to  $X'$ .*

**Proof.** Let us explain how to recapture the full geometry of  $X$  in terms of  $\underline{\mu}_r = \underline{\mu}_r^X$ . To grasp the idea, let us look at the function  $\varphi(x) = \mu(B(\rho, x))$ , where  $B(\rho, x)$  denotes the open ball around  $x$  of a fixed radius  $\rho$ . We want to show that the pushforward measure  $\mu_* = \varphi_*(\mu)$  on  $\mathbb{R}$  can be reconstructed from  $\underline{\mu}_r$ . To see this, observe that the *first moment* of  $\mu_*$ , i.e.,

$$\int_{\mathbb{R}} t \, d\mu_* = \int_X \varphi(x) \, d\mu$$

is readily available in terms of  $\underline{\mu}_2$ , since

$$\int_X \varphi(x) \, d\mu = \underline{\mu}_2 \{m \in \mathbb{R} = M_2 : m \leq \rho\}.$$

Similarly, we compute the moments  $\int_{\mathbb{R}} t^{r-1} \, d\mu_* = \int_X \varphi^{r-1}(x) \, d\mu$  using the obvious formula

$$\int_X \varphi^{r-1}(x) \, d\mu = \underline{\mu}_r \{m_{ij} \in M_r : m_{1j} \leq \rho, j = 2, \dots, r\}$$

and conclude that

$$\underline{\mu}_r^X = \underline{\mu}_r^{X'} \Rightarrow \int_{\mathbb{R}} t^{r-1} (d\mu_* - d\mu'_*) = 0$$

(where we put “ $d$ ” in front of “ $\mu$ ” following the phonetic tradition accepted by analysts). Now, two measures on  $\mathbb{R}$  with compact supports and having equal moments for all  $r$  are equal, since polynomials  $\sum_{i=0}^r a_i t^i$  are dense in the space of continuous functions on compact subsets in  $\mathbb{R}$ . Therefore, the functions  $\varphi(x) = \mu(B(\rho, x))$  on  $X$  and  $\varphi'(x) = \mu'(B(\rho, x'))$  on  $X'$  are equally distributed. It implies that if  $X$  contains an  $r$ -ball of  $\mu$ -measure  $t$ , then so does  $X'$  for almost all (with respect to  $\mu$ )  $t \in \mathbb{R}$ .

All of this obviously applies to the annuli

$$A(x) = A(x, \rho, R) = \{y \in X : \rho \leq \text{dist}(x, y) \leq R\},$$

where one reconstructs the pushforward of  $\mu$  under the function  $\psi(x) = \mu(A(x))$ . Furthermore, one can consider pairs of annuli and take the pair of functions  $\psi_i(x) = \mu(A(\rho_i, R_i, x))$ ,  $i = 1, 2, \dots$ . Such a pair pushes the measure  $\mu$  from  $X$  to some  $\mu_*$  on  $\mathbb{R}^2$  where the moments  $\int_{\mathbb{R}^2} t_1^{r_1-1} t_2^{r_2-1} d\mu_*$  can be computed as earlier in terms of  $\underline{\mu}_r$  for  $r = r_1 + r_2$ . Then one generalizes to finite systems of annuli  $A(\rho_i, \rho_{i+1}, x)$  for some  $0 \leq \rho_1 \leq \dots \leq \rho_i \leq \dots \leq \rho_n$  and concludes that the measures  $\underline{\mu}_r$  recapture the push forward of  $\mu$  under the map  $\phi$  from  $X$  to the space of measures on  $\mathbb{R}$ , where  $x$  goes by  $\phi$  to the pushforward of  $\mu$  under the function  $d : y \mapsto \text{dist}(y, x)$  on  $X$ . It follows that for each  $x \in X$ , there exists a point  $x' \in X$  such that the functions  $d(y') = \text{dist}_{X'}(y', x')$  pushes  $\mu'$  to the measure on  $\mathbb{R}$  equal to the pushforward of  $\mu$  under  $d$ .

Such an  $x'$  is constructed as the limit of a sequence of points giving equalities to the measures of annuli, where the convergence is obtained for a subsequence via the following obvious

**3½.6. Subsequence lemma:** *Let  $y_i$  be a sequence of points in an mm-space  $Y$  of finite mass. Then either  $y_i$  admits a convergent subsequence, or there exists  $\varepsilon > 0$  such that the  $\varepsilon$ -balls around  $y_i$  have  $\mu_Y(B(y_i, \varepsilon)) \rightarrow 0$  for  $i \rightarrow \infty$ .*

This lemma applies to sequences in  $X'$  where the relevant point  $x \in X$  must have  $\mu_X(B(x, \varepsilon)) > 0$  for all  $\varepsilon > 0$ . This is indeed the case, since we assume here that  $X = \text{Supp } \mu_X$  (as was indicated earlier).

Finally, we generalize the discussion above to finite configurations  $(x_1, \dots, x_k)$  of points in  $X$ , where we recapture the pushforward of  $\mu$  under the map  $X \rightarrow \mathbb{R}^k$  for  $y \mapsto \{\text{dist}(y, x_i)\}_{i=1, \dots, k}$ . Namely, we show in this way that for each  $k$ -tuple of points  $x_1, \dots, x_k$  in  $X$ , there exist points  $x'_1, \dots, x'_k$  in  $X'$  such that

$$\text{dist}_X(x_i, x_j) = \text{dist}_{X'}(x'_i, x'_j)$$

and the measures  $\mu$  and  $\mu'$  have equal pushforwards in  $\mathbb{R}^k$  under the maps

$$y \mapsto \{\text{dist}(y, x_i)\} \quad \text{and} \quad y' \mapsto \{\text{dist}(y', x'_i)\}.$$

We conclude the proof of the theorem by taking a dense sequence  $x_1, x_2, \dots, x_i, \dots$  in  $X$  and constructing a sequence  $x'_1, x'_2, \dots, x'_i, \dots$  in  $X'$  with the above such that  $\text{dist}_{X'}(x'_i, x'_j) = \text{dist}_X(x_i, x_j)$  for all  $i, j = 1, 2, \dots$  and the maps  $y'_k : X' \rightarrow \mathbb{R}^k$  for  $y' \mapsto \{\text{dist}(y', x'_i)\}_{i=1, \dots, k}$  push forward  $\mu'$  to the measure on  $\mathbb{R}^k$  equal to the pushforward  $\mu_*$  of  $\mu$  under the corresponding map  $X \rightarrow \mathbb{R}^k$ . Then the map  $\{x_i\} \rightarrow \{x'_i\} \subset X'$  extends by continuity to an isometric embedding  $X \rightarrow X'$ , where the equalities  $\mu'_k = \mu_k$ ,  $k = 1, 2, \dots$ , show that this map pushes forward  $\mu$  to  $\mu'$ . Thus, it is the required isomorphism  $X \simeq X'$ .

**Corollary:**  $\square_\lambda$  is a metric.

**Proof.** The only point to check is the implication

$$\square_\lambda(X, X') = 0 \Rightarrow X \simeq X'.$$

But it is obvious that the measures  $\underline{\mu}_r^X$  are independent of parametrization and continuous in functions  $d : [0, m]^2 \rightarrow \mathbb{R}$  with respect to  $\square_\lambda$  for each  $\lambda \geq 0$ . Hence

$$\square_\lambda(X, X') = 0 \Rightarrow \underline{\mu}_r^X = \underline{\mu}_r^{X'},$$

and the theorem applies.

This corollary justifies the notion of the  $\square_\lambda$ -limit: if it exists, then it is unique in our category of mm-spaces.

**3½.7. Another proof of the reconstruction theorem.** The following elegant (albeit less elementary) argument was suggested to me by A. Vershik. Let  $M_\infty$  be the space of infinite matrices  $\{d_{ij}\}$  for  $i, j = 1, 2, \dots$ , and let  $X^\mathbb{N}$  denote the space of infinite sequences  $x_i \in X$ ,  $i \in \mathbb{N}$ , with the product measure  $\mu \times \mu \times \dots$ , where the original measure  $\mu$  in  $X$  is assumed to be normalized. Then we map  $X^\mathbb{N}$  to  $M_\infty$  as before by sending  $\{x_i\}$  to  $\{d_{ij} = \text{dist}_X(x_i, x_j)\}$ , and we denote by  $\underline{\mu}_\infty$  the pushforward of the measure  $\mu \times \mu \times \dots$  on  $M_\infty$  under this map.

*Step A.* If  $\underline{\mu}_r^X = \underline{\mu}_r^{X'}$  for each  $r = 1, 2, \dots$ , then

$$\underline{\mu}_\infty^X = \underline{\mu}_\infty^{X'}.$$

In fact, the measure  $\underline{\mu}_{r+1}^X$  goes to  $\underline{\mu}_r^X$  under the projection  $M_{r+1} \rightarrow M_r$ , forgetting the last column and row, and the measure  $\underline{\mu}_\infty^X$  appears as the projective limit of the measures for the tower of measure

spaces

$$\cdots \rightarrow (M_r, \underline{\mu}_r^X) \rightarrow (M_{r-1}, \underline{\mu}_{r-1}^X) \rightarrow \cdots$$

*Step B.* A generic sequence  $\{x_1, x_2, \dots, \} \in X^{\mathbb{N}}$  is equidistributed in  $(X, \mu)$ , where “generic” means “almost surely” for the product measure on  $X^{\mathbb{N}}$  (see 3 $\frac{1}{2}$ .22).

*Step C.* If  $\underline{\mu}_{\infty}^X = \underline{\mu}_{\infty}^{X'}$ , then there exist equidistributed sequences  $x_i \in (X, \mu)$  and  $x'_i \in (X', \mu')$  such that  $\text{dist}(x_i, x_j) = \text{dist}'(x'_i, x'_j)$  for all  $i, j \in \mathbb{N}$ .

This means that there are points in  $X^{\mathbb{N}}$  and  $(X')^{\mathbb{N}}$  which correspond to *equidistributed* sequences in  $X$  and  $X'$  with equal images in  $M_{\infty}$ . This is obvious, since the images of sets of generic points from  $X$  have full measure in  $M_{\infty}$  and the same is true for  $X'$  which correspond to *equidistributed* sequences in  $X$  and  $X'$ .

*Step D.* The map  $x_i \rightarrow x'_i$  is isometric on our sequences, and it extends by continuity to an isometry  $X \rightarrow X'$ . And since these sequences are equidistributed, this isometry sends  $\mu$  to  $\mu'$ .

**Remark:** The reader may feel perplexed by how the seemingly spineless argument above could take care of such technical tools as the Weierstrass approximation theorem used in the first proof. But in fact one knows that this theorem follows from a suitably interpreted version of the law of large numbers, and the reader is invited to find this relation by comparing the two proofs of the reconstruction theorem.

A. Vershik suggested the following questions and remarks (a)-(d) to me.

(a) Positive matrices in  $M_{\infty}$  satisfying the triangle inequality are (essentially) metrics on  $\mathbb{N}$ , and the probability measures on  $M_{\infty}$  can be interpreted as random metrics on  $\mathbb{N}$ . The measures of the form  $\underline{\mu}_{\infty}^X$  are invariant under the infinite permutation group  $S_{\infty}$  and are ergodic under this action, since the shift is ergodic on  $X^{\mathbb{Z}}$ . Can one directly describe these measures in terms of the space  $M_{\infty}$ ?

(b) One can think of ergodic  $S_{\infty}$ -invariant measures on  $M_{\infty}$  as generalized (by how much?) mm-spaces and try to define basic mm invariants for them, such as the covering number, etc. (see 3 $\frac{1}{2}$ .F+).

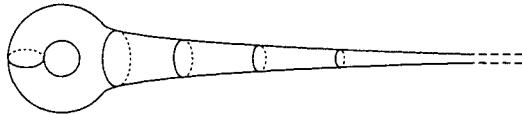
(c) One can define various natural metrics on measures on  $M_{\infty}$ , e.g., using the Monge-Kantorovich-Rubenstein transportation metric on measures on  $M_r$  (compare 3 $\frac{1}{2}$ .10) and letting  $r \rightarrow \infty$ . (These metrics refine the structure of our space  $(\mathcal{X}, \square_1)$ , compare 3 $\frac{1}{2}$ .10).

(d) The measures with the “maximal entropy” on  $M_{\infty}$  may be related to the Uryson space (see 3.11 $\frac{2}{3}$ +).

## C. Geometry of measures in metric spaces

In order to clarify the idea of  $\square$ -convergence of spaces, we want to compare it to the more traditional notion of convergence of measures in a fixed metric space  $X$ . Here, we bring together some relevant facts and refer to [Fed]GMT and [Parth] for missing details and further information.

**3 $\frac{1}{2}$ .8. Thick-thin decomposition and compact exhaustion of mm-spaces.** We think of  $X$  as being *thin* at a point  $x \in X$  on the scale  $\rho$  if the ball  $B(x, \rho)$  has “small” measure, and we call the point “thick” otherwise. For example, a complete Riemannian manifold of finite volume is getting thinner and thinner as we go to infinity.



Also, the sequence of cubes

$$[0, 1], [0, 1]^2, [0, 1]^3, \dots, [0, 1]^n, \dots$$

gets thinner at each point with the growth of dimension but in a geometrically different way.

To make the concept of “thick-thin” precise, we define

$$\text{Tn } X(\rho, \kappa) = \{x \in X : \mu(B(x, \rho)) < \kappa\}$$

and

$$\text{Tk } X(\rho, \kappa) = X \setminus \text{Tn } X = \{x \in X : \mu(B(x, \rho)) \geq \kappa\}.$$

Then for a given positive function  $\kappa(\rho) > 0$ , we set

$$\text{Tk } X(\kappa(\rho)) = \bigcap_{0 < \rho \leq 1} \text{Tk } X(\rho, \kappa(\rho)),$$

and we observe that if  $\mu(X) < \infty$ , then the subset  $\text{Tk } X(\kappa(\rho)) \subset X$  is compact for each function  $\kappa(\rho) > 0$ . This follows trivially from the subsequence lemma of the previous section.

Next, we observe that  $\mu(\text{Tn } X(\rho, \kappa)) \rightarrow 0$  for each fixed  $\rho > 0$  and  $\kappa \rightarrow 0$ , again assuming  $\mu(X) < \infty$ . It follows that there exists a decreasing sequence of positive functions  $\kappa_i(\rho) > 0$  (converging to zero) such that the compact subsets

$$\text{Tk } X(\kappa_1(\rho)) \subset \text{Tk } X(\kappa_i(\rho)) \subset \dots$$

exhaust all measure of  $X$ , i.e.,

$$\mu(\text{Tk } X(\kappa_i(\rho))) \rightarrow \mu(X)$$

for  $i \rightarrow \infty$ . Then this trivially implies for all (possibly infinite) mm-spaces the following standard fact.

**Compact exhaustion of measures.** *Every mm-space  $X$  admits an increasing sequence of compact subsets  $X_1 \subset X_2 \subset \dots$  such that every  $Y \subset X$  satisfies  $\mu(Y \cap X_i) \rightarrow \mu(Y)$  as  $i \rightarrow \infty$ .*

**Almost compact partitions.** Every compact subset  $Y$  can be covered by  $\delta$ -small parts, for each  $\delta > 0$ , and all measure of  $Y$  up to  $\varepsilon$  can be contained in a union of disjoint  $\delta$ -small subsets. Thus, we arrive at the following

**$\varepsilon$ -Partition lemma:** *For arbitrary  $\delta > 0$  and  $\varepsilon > 0$ , there exist pairwise disjoint compact subsets  $K_1, \dots, K_N$  such that  $\text{diam}(K_i) \leq \delta$  and their complement  $U = X \setminus \bigcup_{j=1}^N K_j$  has  $\mu(U) < \varepsilon$ .*

**3 $\frac{1}{2}$ .9. Convergence of measures.** A sequence of finite (i.e., of finite mass) measures  $\mu_i$  is said to *converge* to  $\mu$  if  $\mu_i(f) \rightarrow \mu(f)$  for every bounded, positive, continuous function  $f$  on  $X$ , where  $\mu(f)$  stands for  $\int_X f d\mu$ . (If we allow infinite  $\mu_i$ , then we require that each point  $x \in X$  admit a neighborhood  $U \subset X$  such that  $\mu_i(U) < \infty$  and  $\mu_i|_U \rightarrow \mu|_U$ . This agrees with the previous definition for finite  $\mu_i$  via partitions of unity).

**The metric  $\text{Lid}_b$ .** Set

$$\text{Lid}_b(\mu, \mu') = \sup_f |\mu(f) - \mu'(f)|$$

for  $b > 0$ , where  $f$  runs over all *1-Lipschitz* functions  $f: X \rightarrow [0, b]$ . Clearly, these are true metrics on the space  $\mathcal{M}(X)$  of finite measures on  $X$ , and they are all mutually bi-Lipschitz equivalent. It is also not hard to see that  $\mathcal{M}(X)$  is complete for  $\text{Lid}_b$ . In fact,  $\mathcal{M}(X)$  is *Polish*, since measures with finite supports are (obviously) dense in  $\mathcal{M}(X)$ . Furthermore, *if  $X$  is compact, then each  $\mathcal{M}_m = \{\mu \in \mathcal{M}(X) : \mu(X) \leq m\}$  is compact*.

**Lid-convergence.** Obviously, convergence of  $\mu_i \rightarrow \mu$  implies  $\text{Lid}_b$ -convergence for each  $b < \infty$ , provided that  $\mu(X) < \infty$ . *Conversely, Lid-convergence for a given  $b > 0$  implies convergence.* This follows via the compact exhaustion of  $\mu$ , since every continuous function is uniformly continuous on each compact subset  $Y \subset X$ , and so it can be uniformly approximated on  $Y$  by a Lipschitz function.

**The metric  $\text{di}_\lambda$  on measures.** The distance  $\text{di}_\lambda$  for  $\lambda \geq 0$  between finite measures  $\mu$  and  $\mu'$  on a metric space  $X$  is defined (à la Hausdorff) as the

infimal  $\varepsilon$  for which the  $\mu$ -measure of the  $\varepsilon$ -neighborhood of each  $X_0 \subset X$  is at least  $\mu'(X_0) - \lambda\varepsilon$  and vice-versa, i.e.

$$\mu(U_\varepsilon(X_0)) \geq \mu'(X_0) - \lambda\varepsilon \quad \text{and} \quad \mu'(U_\varepsilon(X_0)) \geq \mu(X_0) - \lambda\varepsilon$$

for all Borel subsets  $X_0 \subset X$ . Here again, the metrics  $\text{di}_\lambda$  are all mutually equivalent for  $\lambda > 0$ . A little thought shows that they are equivalent to  $\text{Lid}_b$ . (In fact, they could be defined in the spirit of  $\text{Lid}_b$  with the supremum taken over truncated distance functions to subsets  $Y \subset X$ .)

The metric  $\text{di}_0$  is significantly different from the rest of the  $\text{di}_\lambda$ . For example, it obviously majorizes the Hausdorff distance between the supports of the measures. Also,  $\text{di}_0$  majorizes  $\text{Lid}_b$  for all  $b$ . In fact,

$$|\mu(f) - \mu'(f)| \leq (\text{Lip}(f)) \text{di}_0(\mu, \mu'), \tag{*}$$

as follows from  $(\star)$  below.

**3½.10. The transportation metric  $\text{Tra}_\lambda$ .** Let us think of measures as piles of stones in  $X$  and try to transport one such pile  $\mu$  to the location (support) of another pile  $\mu'$ , where we have to replace each  $\mu'$ -stone by a  $\mu$ -stone of equal mass. In doing this, we insist that each stone be moved by the distance  $\leq \varepsilon$ , and we allow some percentage of stones to remain unmoved. We formalize this by defining a (partial) *transportation* as a measure  $\nu$  on  $X \times X$  whose projections (i.e., pushforwards) to  $X$ , say  $\underline{\nu}$  and  $\underline{\nu}'$  satisfy  $\underline{\nu} \leq \mu$  and  $\underline{\nu}' \leq \mu'$  (where the inequality  $\mu_1 \leq \mu_2$  means that  $\mu_2 = \mu_1 + \mu_3$  for some measure  $\mu_3$ ). Clearly  $\nu(X \times X) \leq \min(\mu(X), \mu'(X))$ , and the maximum of the two numbers  $\mu(X) - \nu(X \times X)$  and  $\mu'(X) - \nu(X \times X)$  is called the *deficiency* of  $\nu$ . Finally,  $\nu$  is called an  $\varepsilon$ -*transportation* if it is supported in the subset

$$Y_\varepsilon = \{(x, x') \in X \times X : \text{dist}_X(x, x') \leq \varepsilon\}$$

Now we define  $\text{Tra}_\lambda(\mu, \mu')$  as the infimal  $\varepsilon$  for which there exists an  $\varepsilon$ -transformation  $\nu$  (from  $\mu$  to  $\mu'$ ) of deficiency  $\leq \lambda\varepsilon$ . (According to this definition, we are allowed to break stones into smaller pieces and to transport different pieces of the same stone to different locations.) Clearly, if  $\text{Tra}_\lambda(\mu, \mu') \leq \varepsilon$ , then

$$\text{Lid}_b(\mu, \mu') \leq \varepsilon M + 2b\lambda\varepsilon, \tag{+}$$

where  $M \stackrel{\text{def}}{=} \max(\mu(X), \mu(X')) - \lambda\varepsilon$  refers to the mass  $M = \nu(Y_\varepsilon)$  of the optimal  $\varepsilon$ -transformation  $\nu$ . (To visualize  $(+)$ , split  $\mu = \mu_\varepsilon + \underline{\nu}$  and  $\mu' = \mu'_\varepsilon + \underline{\nu}'$ , where  $\underline{\nu}(X) = \underline{\nu}'(X) = M$ , and where  $\nu$  transports all of  $\underline{\nu}$  to  $\underline{\nu}'$ . This transport moves points by distances  $\leq \varepsilon$ , and so  $|\underline{\nu}(f) - \underline{\nu}'(f)| \leq |\nu|\varepsilon$

for every 1-Lipschitz function  $f$ . On the other hand, since  $|f| \leq b$ , the leftovers  $\mu_\varepsilon(f)$  and  $\mu'_\varepsilon(f)$  are both bounded by  $\lambda\varepsilon$ .

It is also easy to see that  $\text{Tra}_\lambda$  induces the same topology as  $\text{di}_\lambda$  (and hence  $\text{Lid}_b$ ). Namely,  $\text{di}_\lambda$ -convergence  $\mu_i \rightarrow \mu$  implies  $\text{Tra}_\lambda$ -convergence. To see this, take small  $K_1, \dots, K_N$  with  $\text{diam } K_j \leq \delta$  and  $\mu(X \setminus \bigcup_{j=1}^N K_j) \leq \kappa$  for small (and eventually going to zero)  $\delta$  and  $\kappa$  as in the  $\varepsilon$ -partition lemma above. When  $\mu_i$  approaches  $\mu$  in the  $\text{di}_\lambda$ -metric, small disjoint neighborhoods  $U_j$  of  $K_j$  have  $\mu_i(U_j)$  close to that of  $\mu(K_j)$ . In fact, for large  $i$ , we can make the total error  $\sum_{j=1}^N |\mu(K_j) - \mu_i(U_j)|$  as small as we want, say  $\leq \kappa$ . Then we transport as much as we can of the  $\mu_i$ -measure of each  $U_i$  to the  $\mu$ -measure of  $K_j$ , thus transporting all but  $3\kappa$  of the full  $\mu_i(X)$ , where we assume (as we may) that  $|\mu_i(X) - \mu(X)| \leq \kappa$ . This transportation moves points by at most  $\text{diam}(U_i)$ , which can be taken close to  $\delta$ , say  $\leq 2\delta$ . Thus, we bound  $\text{Tra}_\lambda(\mu, \mu_i)$  by  $\varepsilon \leq 2\delta + 3\kappa\lambda^{-1}$ .

Next, we want to obtain a specific bound on  $\text{Tra}_\lambda$  by  $\text{di}_\lambda$ , and we do this by appealing to the following

**König's matching theorem.** *Let  $\mu$  and  $\mu'$  be measures on  $X$  and  $X'$ , respectively, and let  $Y \subset X \times X'$  be a closed subset. Then the following condition is sufficient (and obviously necessary) for the existence of a partial transportation measure  $\nu$  of a given mass with support in  $Y$ :*

**Matching property:** *For every Borel subset  $X_0 \subset X$ , the  $Y$ -match  $X'_0 \subset X'$  defined as the projection of  $(X_0 \times X') \cap Y$  to  $X'$  satisfies*

$$\mu'(X'_0) - \mu(X_0) \geq m - \mu(X).$$

**Remarks:** (a) The matching property looks asymmetric for  $X \leftrightarrow X'$ , but a little thought reveals the actual symmetry.

(b) The classical König theorem refers to finite spaces (see [Lova-Plum] and [Bol-Var]), and the general case then can be derived by an obvious approximation of  $\mu$  and  $\mu'$  by measures with finite supports. (We do not need the finer aspect of the classical König theorem which delivers an *integer-valued* transportation  $\nu$  for integer valued  $\mu$  and  $\mu'$ . In fact, the most interesting case refers to measures consisting of atoms of unit mass.)

**Corollary:** *The metrics  $\text{Tra}_\lambda$  and  $\text{di}_\lambda$  are equal for all  $\lambda \geq 0$ ,*

$$\text{Tra}_\lambda(\mu, \mu') = \text{di}_\lambda(\mu, \mu') \tag{*}$$

*for all measures  $\mu$  and  $\mu'$ .*

**Proof.** The inequality  $\text{di}_\lambda(\mu, \mu') \leq \varepsilon$  is equivalent to the  $Y_\varepsilon$ -matching condition for transportations from  $\mu$  to  $\mu'$  of mass  $m = \mu(X) - \lambda\varepsilon$  and from  $\mu'$  to  $\mu$  of mass  $m' = \mu'(X') - \lambda\varepsilon$ .

**Applications to  $\text{Lid}_b$  and  $\square_\lambda$ .** (a) Bringing together  $(*)$  with  $(+)$  above gives an effective bound on  $\text{Lid}_b$  by  $\text{di}_\lambda$ . Namely,

$$\text{di}_\lambda(\mu, \mu') \leq \varepsilon \Rightarrow \text{Lid}_b(\mu, \mu') \leq \varepsilon M + 2b\lambda\varepsilon$$

for  $M = \max(\mu(X), \mu'(X)) - \lambda\varepsilon$ . For example, if  $\mu(X) \leq \mu(X') \leq 1$ , then

$$\text{Lid}_1 \leq 3 \text{Tra}_1 = 3 \text{di}_1.$$

(b) *Convergence  $\mu_i \rightarrow \mu$  implies the  $\square_\lambda$ -convergence of the mm-spaces,*

$$(X, \text{dist}, \mu_i) \rightarrow (X, \text{dist}, \mu).$$

In fact, if  $\text{Tra}_1(\mu, \mu') \leq \varepsilon$ , then we have a  $\nu$  on  $Y_\varepsilon \subset X \times X$  which projects to measures  $\underline{\nu} \leq \mu$  and  $\underline{\nu}' \leq \mu'$  which  $\varepsilon$ -approximate  $\mu$  and  $\mu'$ . We add the error  $\kappa = (\mu - \underline{\nu}) \times (\mu' - \underline{\nu}')$  to  $\nu$  and even the resulting  $\nu_+ = \nu + \kappa$  parametrizes  $\mu$  and  $\mu'$ , i.e., one has  $\underline{\nu}_+ = \mu$  and  $\underline{\nu}'_+ = \mu'$ . Then we parametrize  $\nu_+$  by  $[0, m]$  for  $m = \nu_+(X \times X)$  and observe that the pullbacks of  $d$  and  $d'$  of  $\text{dist}(X, X')$  satisfy  $\square_1(d, d') \leq 2\varepsilon$ .

(c) **Exercise:** Consider finite measures  $\mu$  and  $\mu'$  with  $\mu'(X) = \mu(X)$ , and define the *Kantorovich–Rubenstein* distance (compare [Kantor], [Gan–McCann], [Levin])

$$\text{Tran}(\mu, \mu') = \inf_{\nu} \int \text{dist}(x, x') d\nu,$$

where  $\nu$  runs over all transportations (measures)  $\nu$  on  $X \times X$  of zero deficiency. Show that

$$\text{Tran}(\mu, \mu') = \text{Lid}_\infty(\mu, \mu').$$

Observe that these two are true *everywhere finite* metrics iff  $\text{diam}(X) < \infty$ .

**3½.11. Induced Minkowski measures on subsets  $Y \subset X$ .** A subset  $Y$  in an mm space is called *Minkowski regular* if the normalized measures  $\mu_\varepsilon$  on the  $\varepsilon$ -neighborhoods of  $Y$  converge as  $\varepsilon \rightarrow 0$ , where  $\mu_\varepsilon$  denotes the measure  $(\mu|_{U_\varepsilon})/\mu(U_\varepsilon)$  and  $U_\varepsilon = U_\varepsilon(Y)$ . This limit is a probability measure supported on  $Y$ , called the *induced Minkowski measure*. This is of particular interest where  $\mu(Y) = 0$ , and so naively restricting  $\mu$  to  $Y$  gives us the zero measure. Also notice that one can define *an* induced measure on  $Y$  by taking the limit of a *subsequence*  $\mu_{\varepsilon_i}$  in the case where  $Y$  is *not* Minkowski

regular. Such sublimits exist in many cases as the families of measures  $\mu_\varepsilon$ ,  $\varepsilon \rightarrow 0$ , are typically  $d_{1+}$ -precompact.

**Examples and exercises.** (a) Show that every compact smooth submanifold  $Y$  in a Riemannian manifold is Minkowski regular and that the induced Minkowski measure (from the Riemannian measure on  $X$ ) equals the normalized Riemannian measure on  $Y$ .

(b) Show that every compact semialgebraic subset  $Y \subset X = \mathbb{R}^n$  is Minkowski regular.

## D. Basic geometry of the space $\mathcal{X}$

We stick to  $\lambda = 1$  (since all  $\square_\lambda$ -metrics for  $\lambda > 0$  are equivalent) and denote by  $\mathcal{X}$  the space of isomorphism classes of mm-spaces of *finite mass* with the metric  $\square_1$ . We agree that  $\mathcal{X}$  contains a unique element of mass zero denoted by  $\mathbf{0}$ .

**3½.12. Union lemma:** *Let  $X_i \in \mathcal{X}$  satisfy  $\square_1(X_{i+1}, X_i) \leq 2^{-i}$ . Then there exists a Polish space  $\overline{X}$  and a sequence of measures  $\overline{\mu}_i$  on  $\overline{X}$  such that the  $\overline{\mu}_i$  converge to some  $\overline{\mu}$  on  $\overline{X}$ , and where each  $(X_i, \text{dist}_i, \mu_i)$  is isomorphic to  $(\overline{X}, \overline{\text{dist}}, \overline{\mu}_i)$ .*

**Proof.** Consider parametrizations  $p_i : [0, m_i] \rightarrow X_i$  and  $p'_i : [0, m'_i = m_{i+1}] \rightarrow X_{i+1}$  responsible for the inequality  $\square_1(X_{i+1}, X_i) \leq 2^{-i}$ , and let  $T_i \subset [0, m_i] \cap [0, m'_i]$  be the subset where the pullbacks  $d_i$  and  $d'_i$  of the metrics  $\text{dist}_i$  and  $\text{dist}_{i+1}$  are  $2^{-i}$ -close. Say that points  $x_i \in X_i$  and  $x'_{i+1} \in X_{i+1}$  are  $\square$ -neighbors if  $\exists t \in T$  such that  $p_i(t) = x$  and  $p'_i(t) = x'$ . Then we consider the disjoint union  $X = X_1 \sqcup X_2 \sqcup \dots$  and take the supremal metric  $\overline{\text{dist}}$  on  $X$  such that  $\text{dist}|_{X_i} = X_i$  and  $\text{dist}(x_i, x'_{i+1}) \leq 2^{-i+1}$  for all pairs of neighbors  $x_i \in X_i$ ,  $x'_{i+1} \in X_{i+1}$ , and all  $i = 1, 2, \dots$ . It is obvious that the  $\text{Tra}_1$ -distance between the measures  $\overline{\mu}_i$  and  $\overline{\mu}_{i+1}$  on  $X$  corresponding to  $\mu_i$  and  $\mu_{i+1}$  under the embeddings  $X_i, X_{i+1} \subset X$  does not exceed  $2^{-i+2}$ . Thus the  $\overline{\mu}_i$  form a Cauchy sequence which converges to some  $\overline{\mu}$  on the completion  $\overline{X}$  of  $X$ .

**Corollary:** *The space  $(\mathcal{X}, \square_1)$  is complete and is therefore a Polish metric space.*

**3½.13. A remark on the normalization of measures and subspaces  $\mathcal{X}_m$  and  $\mathcal{X}_{\leq m}$  in  $\mathcal{X}$ .** The group  $\mathbb{R}_+^*$  naturally acts on  $\mathcal{X}$  by  $X = (X, \text{dist}, \mu) \mapsto (X, \text{dist}, r\mu)$  for  $r \in \mathbb{R}_+^*$ , and the function  $X \mapsto \mu(X)$  on  $\mathcal{X}$

is homogeneous with respect to this action. Putting this with  $r = m^{-1}$  for  $m = \mu(X)$  is called the *normalization of  $X$  and/or of  $\mu_X$* , since the mass of  $X$  becomes one in the process. The mm-spaces  $X$  with  $\mu(X) = 1$  are called *normalized* or *probability spaces*, in which case the measure  $\mu\{x \in X_0 \subset X\}$  is interpreted as the probability of the event  $x \in X$ .

The space  $\mathcal{X}$  is naturally sliced into the subspaces  $\mathcal{X}_m$ ,  $m \in \mathbb{R}_+$ , consisting of  $X$  with  $\mu(X) = m$ . Every such  $X$  can be parametrized by the segment  $[0, m]$ , and the metric  $\underline{\square}_1$  on  $\mathcal{X}_m$  descends from  $\square_1$  on functions  $d: [0, m]^2 \rightarrow \mathbb{R}_+$ . The relevant functions  $d$  form a convex subset  $D$  and  $\square_1$  is, obviously, a path metric on  $D$ . It follows that  $\underline{\square}_1$  on  $\mathcal{X}$  is also a path metric. Then it is clear from the definition of  $\underline{\square}_1$  on  $\mathcal{X}$  that it is a path metric on  $\mathcal{X}$ .

When dealing with convergence and (pre)compactness in  $\mathcal{X}$ , it is convenient to restrict to the subspace  $\mathcal{X}_{\leq m} = \{X \subset \mathcal{X} : \mu(X) \leq m\}$  (see below). This  $\mathcal{X}_{\leq m}$  is, like  $\mathcal{X}_m$ , *geodesically convex* (i.e. *path metric*) in  $\mathcal{X}$ . We note in passing that the function  $X \mapsto \mu(X)$  is  $\underline{\square}_1$ -continuous on  $\mathcal{X}$ , and so  $\mathcal{X}_m$  and  $\mathcal{X}_{\leq m}$  are closed as well as geodesically convex subspaces in  $\mathcal{X}$ .

Everything we do with mm-spaces with finite measure can be reduced to the normalized case where the statements are somewhat easier. However, we allow all  $m = \mu(X)$  since some natural mm-spaces are not normalized. For example, the mass of the unit ball  $B(1) \subset \mathbb{R}^n$  is far from one. In fact, it is about  $n^{-n/2}$ , while  $\mu(B(R)) = 1$  is achieved for  $R \approx \sqrt{n}$ .

**3 $\frac{1}{2}$ .14. Complexity of mm spaces and (pre-)compactness criteria for subsets  $\mathcal{Y} \subset \mathcal{X}$  (compare Ch. 5A).** The basic measure of the overall complexity of a finite mm space  $X$ , besides its mass  $m = \mu(X)$ , is reflected in the pair of numbers  $N$  and  $D$  depending on given  $\delta, \varepsilon > 0$ , such that  $X$  can be covered by  $N$  subsets  $K_i$ ,  $i = 1, \dots, N$ , of diameter  $\leq \delta$  and such that  $\mu(X \setminus \bigcup_{i=1}^N K_i) \leq \varepsilon$  and  $\text{diam}(\bigcup_{i=1}^N K_i) \leq D$ . We express the existence of such an up-to- $\varepsilon$  covering by writing

$$\text{co}(X, \delta, \varepsilon) \leq (N, D).$$

Given an up-to- $\varepsilon$  covering, we can obviously replace  $K_i$  by mutually disjoint compact subsets  $K_i^\circ \subset K_i$  with  $\bigcup_{i=1}^N K_i^\circ \geq \mu(\bigcup_{i=1}^N K_i - \varepsilon_0)$  for a given  $\varepsilon_0 > 0$ , say for  $\varepsilon_0 = \varepsilon$ . This allows an approximation of the underlying measure  $\mu$  by measures with finite supports. In fact, we can replace each  $K_i^\circ$  by a single atom situated in  $K_i^\circ$  of mass  $m_i = \mu(K_i^\circ)$ . Thus, we get  $\mu_N$  with  $N$  atoms such that  $\text{Tra}_1(\mu, \mu_N) \leq \varepsilon' = \max(\delta, 2\varepsilon)$ . In particular,  $X$  admits  $2\varepsilon'$  approximation by an  $N$ -point space in the metric  $\underline{\square}_1$ . Conversely, if  $X$  admits an  $\varepsilon$ -approximation by some  $X_N$  consisting of  $N$  atoms and having

$\text{diam}(X_N) = D_N$ , then

$$\text{co}(X, 3\varepsilon', 3\varepsilon') \leq (N, D + 3\varepsilon)$$

as an obvious argument shows.

Finally, the complexity of  $X$  can be neatly expressed by looking at the thick-thin decomposition of  $X$  (see 3½.8). Namely, the pair of numbers  $D\text{Tk} = \text{diam Tk } X(\rho, \kappa)$  and  $\mu\text{Tn} = \mu(\text{Tn } X(\rho, \kappa))$  carry the same essential information as  $\text{co}(X; \delta, \varepsilon)$ . In fact,  $\text{Tk } X(\rho, x)$  can be covered by at most  $N \leq \mu(X)/\kappa$  balls of radii  $2\rho$ , which allows a bound on  $\text{co}$  in terms of  $D\text{Tk}$  and  $\mu\text{Tn}$ . Conversely, given the  $K_i^\circ$  above, we take those which have  $\mu(K_i^\circ) \geq \kappa_0$  for  $\kappa_0 = N^{-2}$  and denote by  $\text{Tk}_0$  their union. It is clear that  $\mu(\text{Tk}_0) \geq \mu\left(\bigcup_{i=1}^N K_i^\circ\right) - N^{-1}$  and that  $\text{Tk}_0 \subset \text{Tk } X(\rho, \kappa)$  for  $\rho = \delta$  and  $\kappa = N^{-2}$ . Thus, we control  $D\text{Tk}$  and  $\mu\text{Tn}$  by the covering invariants of  $X$ .

**Proposition:** *Let  $\Delta = \Delta(\varepsilon)$  be an arbitrary positive function defined for  $\varepsilon > 0$  and consider the following three subsets in  $\mathcal{X}$ .*

$\mathcal{Y}_1 = \mathcal{Y}_1(\Delta)$  consisting of those  $X \in \mathcal{X}$  such that  $\text{co}(X, \varepsilon, \varepsilon) \leq (\Delta(\varepsilon), \Delta(\varepsilon))$  for all  $\varepsilon > 0$ ;

$\mathcal{Y}_2 = \mathcal{Y}_2(\Delta)$  consisting of those  $X \in \mathcal{X}$  which can be  $\varepsilon$ -approximated for all  $\varepsilon > 0$  by spaces  $X_\varepsilon$  with  $\text{diam}(X_\varepsilon) \leq \Delta = \Delta(\varepsilon)$  and  $\text{card}(X_\varepsilon) \leq \Delta = \Delta(\varepsilon)$ ;

$\mathcal{Y}_3 = \mathcal{Y}_3(\Delta)$  consisting of those  $X$  where for every  $\varepsilon$ , there exists  $\kappa \in [\varepsilon, \Delta^{-1}]$  such that  $\text{diam Tk}(\varepsilon, \kappa) \leq \Delta = \Delta(\varepsilon)$  and  $\mu(\text{Tn}(\varepsilon, \kappa)) \leq \varepsilon$ .

Then the intersection  $\mathcal{Y}_i \cap \mathcal{X}_{\leq m}$  is precompact in  $\mathcal{X}$  for each  $i = 1, 2, 3$  and  $m \geq 0$  and the union  $\bigcup_{\Delta} \mathcal{Y}_i(\Delta)$  over all positive functions  $\Delta = \Delta(\varepsilon)$  equals all of  $\mathcal{X}$ , again for each  $i = 1, 2, 3$ .

**Proof.** The space of  $N$ -point spaces with mass  $\leq m$  and diameter  $\leq D$  is, obviously, precompact which implies precompactness of  $\mathcal{Y}_2 \cap \mathcal{X}_{\leq m}$ . Then the discussion above shows that  $\mathcal{Y}_1(\Delta) \subset \mathcal{Y}_2(\Delta')$  for some  $\Delta' = \Delta'(\Delta)$  and  $\mathcal{Y}_3(\Delta) \cap \mathcal{X}_{\leq m} \subset \mathcal{Y}_2(\Delta'')$  for  $\Delta'' = \Delta''(\Delta, m)$ . This yields the precompactness of  $\mathcal{Y}_i \cap \mathcal{X}_{\leq m}$  for  $i = 1, 3$ . And the equality  $\bigcup_{\Delta} \mathcal{Y}_i(\Delta) = \mathcal{X}$  is obvious for  $i = 3$  and hence for  $i = 1, 2$  as well.

**Remark:** It is easy to see that the subsets  $\mathcal{Y}_i(\Delta)$  are  $\sqsubseteq_1$ -closed in  $\mathcal{X}$  for  $i = 1, 2, 3$  and hence the intersection  $\mathcal{Y}_i(\Delta) \cap \mathcal{X}_{\leq m}$  are compact.

**Corollary: Convergence criterion.** *The following conditions are necessary and sufficient for  $\sqsubseteq_1$ -convergence of a sequence  $X_i \in \mathcal{X}$  to some  $X \in \mathcal{X}$ .*

I. The measures  $\underline{\mu}_r^{X_i}$  (see 3 $\frac{1}{2}$ .4) converge as  $i \rightarrow \infty$  to some  $\mu_r$  on  $M_r$  for each  $r = 1, 2, \dots$ .

II. For arbitrary  $\rho > 0$  and  $\kappa > 0$ ,

$$\text{diam}(\text{Tk } X_i(\rho, \kappa)) \leq \text{const} < \infty$$

and there exists a positive function  $\rho(\kappa) > 0$  for  $\kappa > 0$  such that  $\rho(\kappa) \rightarrow 0$  for  $\kappa > 0$  and

$$\mu(\text{Tn } X_i(\rho(\kappa), \kappa)) \leq \varepsilon(\kappa)$$

for some function  $\varepsilon(\kappa) \rightarrow 0$  as  $\kappa \rightarrow 0$  independent of  $i$ .

Furthermore, we can replace II by

III. There exists a function  $\Delta(\varepsilon)$ ,  $\varepsilon > 0$ , such that each  $X_i$  admits  $N \leq \Delta(\varepsilon)$  subsets  $K_{ij} \subset X_i$ ,  $j = 1, \dots, N$  satisfying

1.  $\text{diam}(K_{ij}) \leq \varepsilon$ ,
2.  $\text{diam} \bigcup_{j=1}^N K_{ij} \leq \Delta(\varepsilon)$ ,
3.  $\mu(X_i \setminus \bigcup_{j=1}^N K_{ij}) \leq \varepsilon$ .

**Proof.** Properties II and III allow convergent subsequences, and I implies that these have isomorphic limits, according to the reconstruction theorem (see 3 $\frac{1}{2}$ .5).

**Remark:** The condition I alone does not suffice. For example, the sequence of spaces  $X_i$  consisting of  $i$ -atoms of mass  $i^{-1}$  with unit mutual distances does *not* converge, although the  $\underline{\mu}_r^{X_i}$  converge. A more interesting example is provided by round spheres  $S^i$  with normalized measures. These violate III, but nevertheless the  $\underline{\mu}_r^{S^i}$  converge for each  $r$  (see 3 $\frac{1}{2}$ .18). In general, we may have a sequence  $X_i$  with  $\text{diam}(X_i) \leq D < \infty$  having no convergent subsequence. But there always exists a subsequence  $X^{i_j}$  for which the  $\underline{\mu}_r^{X_{i_j}}$  converge for every  $r$ . (Such subsequences are similar to asymptotic sequences we will introduce in 3 $\frac{1}{2}$ .I but the latter seems to be a better candidate for “ideal mm-spaces”.)

**Examples:** (a) If  $\{X_i\}_{i \in I}$  is a family of compact mm-spaces which is pre-compact in the Hausdorff topology (where we forget about the measures), then it is also  $\sqsubseteq_1$ -precompact, provided that  $\mu_i(X_i) \leq m < \infty$ . This is essentially obvious (as it follows, for example, from the metric version of the union lemma) but is particularly useful and can be applied in particular

to compact manifolds with  $\text{Ricci} \geq -\text{const}$  and  $\text{diam} \leq D$  (see Ch. 5 and [Che-Col]I--III) and to more general spaces with the doubling property (see Appendix B<sub>+</sub>). But nothing essentially new is brought in here along with the measure.

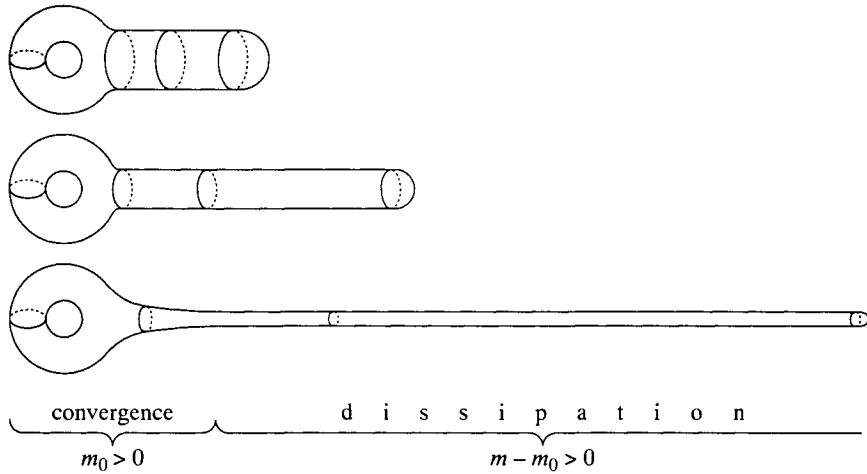
(b) A more interesting picture arises if we do not bound the diameter of our manifolds  $X$  but somehow prevent collapse and the subsequent dissipation of measure (as is present, for instance, in the product  $X = (\varepsilon Y) \times (\varepsilon^{-1} Y)$  for  $\varepsilon \rightarrow 0$ ) by imposing suitable geometric and topological conditions on  $X$ . For example, it follows trivially from Thurston's theory (see [Gro]HMTJ) that the complete connected Riemannian manifolds  $X$  of dimension  $\geq 3$  with  $\text{vol}(X) \leq m$  and pinched negative sectional curvatures,  $0 \geq -\kappa_1 \geq K(X) \geq \kappa_2 > \infty$  form a  $\square_1$ -precompact family. (This is nearly true for  $n = 2$ , where the only catch is a possible nonconnectedness of the thick part of  $X$ , which makes the diameter of  $\text{Tk}(X)$  go to infinity.)



Furthermore, much of the pattern typical for the pinched negative curvature remains valid under the bound  $\text{Ricci} \geq -\text{const}$  if we add suitable *topological* assumptions on  $X$ . For example, if we assume that each  $X$  in question admits an auxiliary complete Riemannian metric with pinched negative curvature and finite volume, we thus impose a nontrivial lower bound on the (volume of) the thick part of (the original metric with  $\text{Ricci} \geq -\text{const}$  on)  $X$  (see [Gro]FRM, [Gro]VBC, and also [Che-Col], [Col]). This allows a subsequence  $X_i$  taken out of the totality of our  $X$ 's which  $\square_1$ -converges on substantial parts of  $X_i$ , i.e., on some subsets  $Y_i \subset X_i$  with  $\mu_i(Y_i) \geq m_0 > 0$ . But some amount of measure may dissipate (in the sense of  $3\frac{1}{2}\cdot J$ ) on some thin, infinitely growing fingers with  $\text{Ricci} \geq 0$ .

However, the full beauty and power of the measure becomes visible only when we look at families of manifolds of *growing* dimension, such as the unit spheres  $S^n$ ,  $n = 1, 2, \dots$ , with normalized measures, which  $\square_1$ -diverge but which nevertheless converge (concentrate) for some weak topology on  $\mathcal{X}$  (see 3½.45).

**3½.15. Lipschitz order on mm-spaces.** Say that  $X$  (*Lipschitz*) *dominates*  $Y$  and write  $X \succ Y$  or  $X \xrightarrow{\text{Lip}_1} Y$  if there exists a 1-Lipschitz map  $X \rightarrow Y$  pushing forward the measure  $\mu_X$  to a measure  $\nu$  on  $Y$  *proportional* to  $\mu_Y$ , i.e.,  $\nu = c\mu_Y$  for some positive constant  $c \geq 1$ .



Here are the basic properties of this order:

- (a) *If two spaces  $X$  and  $Y$  of finite mass satisfy  $X \succ Y \succ X$ , then they are isomorphic.*
- (b) *The Lipschitz order is  $\square_1$ -continuous, i.e., if  $X_i \xrightarrow{\square_1} X$  and  $Y_i \xrightarrow{\square_1} Y$ , then  $X_i \succ Y_i \Rightarrow X \succ Y$ .*
- (c) *Every bounded subset  $\mathcal{X}_0 \subset \mathcal{X}$  is precompact, where ‘‘bounded’’ means that there exists  $X_0 \in \mathcal{X}$  such that  $X \prec X_0$  for all  $X \in \mathcal{X}_0$ .*
- (d) *Every decreasing sequence  $X_1 \succ X_2 \succ \dots \succ X_i \succ \dots$  in  $\mathcal{X}$  converges.*
- (e) *Every bounded increasing sequence in  $\mathcal{X}$  converges.*
- (f) *Every precompact subset in  $\mathcal{X}$  is bounded.*

**Proof.** To prove (a) we introduce the *averaged diameter of an mm space*. This  $AvDi(X)$  is defined as

$$m^{-2} \int_{X \times X} \text{dist}(x, x') d\mu d\mu$$

for  $m = \mu(X)$ . Clearly  $AvDi$  is monotone for the Lipschitz order, and if  $X \succ Y$  while  $AvDi(X) = AvDi(Y) < \infty$ , then the implied 1-Lipschitz map  $X \rightarrow Y$  is an isomorphism. This implies (a) in the case where  $AvDi < \infty$ . In general, we replace  $AvDi$  by the average of  $\varphi(\text{dist}(x, x'))$  for some *bounded*, strictly monotone function  $\varphi(d)$ . This average is necessarily finite, and the reasoning above yields the proof.

**Proof of (b).** Start with the following definition. A map from an mm-space to a metric space, say  $f: X \rightarrow Y$  is called  $\lambda$ -Lipschitz up to  $\varepsilon$  if

$$\text{dist}_Y(f(x), f(x')) \leq \lambda \text{dist}(x, x') + \varepsilon$$

for all  $x, x'$  in a subset  $X_0 \subset X$  with  $\mu(X \setminus X_0) \leq \varepsilon$ .

(3<sub>b</sub>) **me<sub>1</sub>-convergence lemma:** *Let  $X$  be an mm-space with finite measure, let  $Y$  be a Polish space, and let  $f_i: X \rightarrow Y$  be  $\lambda$ -Lipschitz up to  $\varepsilon_i$  Borel maps with a fixed  $\lambda$  and  $\varepsilon_i \rightarrow 0$  for  $i \rightarrow \infty$ . Then the  $f_i$  admit an me<sub>1</sub>-convergent subsequence, provided that the pushforward measures  $(f_i)_*(\mu_X)$  converge to some measure  $\mu$  on  $Y$ .*

**Proof.** Using the Subsequence Lemma (see 3½.6), one achieves convergence on a countable dense set  $A \subset X$ . The resulting map  $f_A: A \rightarrow Y$  is obviously  $\lambda$ -Lipschitz and thus extends by continuity to the desired map  $f: X \rightarrow Y$ .

(3'<sub>b</sub>) **□<sub>1</sub>-convergence lemma:** *Let  $X_i \xrightarrow{\square_1} X$ . Then there exist Borel 1-Lipschitz up to  $\varepsilon_i$  maps  $p_i: X \rightarrow X_i$  and  $q_i: X_i \rightarrow X$  such that  $\varepsilon_i$  as well as  $\text{me}_1(p \circ q, \text{id})$  and  $\text{me}_1(q_i \circ p_i, \text{id})$  converge to zero for  $i \rightarrow \infty$ , and the pushforward measures  $(p_i)_*(\mu_{X_i})$  converge to  $\mu_X$ .*

**Proof.** We map each point in  $X_i$  to some of its neighbors in  $X$  and vice-versa, as we did in the proof of the union lemma (see (1) above). The resulting  $p_i$  and  $q_i$  are clearly what we want.

Now, for convergent  $X_i \rightarrow X$  and  $Y_i \rightarrow Y$ , we take  $p_i: X \rightarrow X_i$  and  $q_i: Y_i \rightarrow Y$  and then observe that the maps  $q_i \circ p_i: X \rightarrow Y$  satisfy the assumption of (3<sub>b</sub>) with  $\lambda = 1$  and  $\mu = \mu_Y$ .

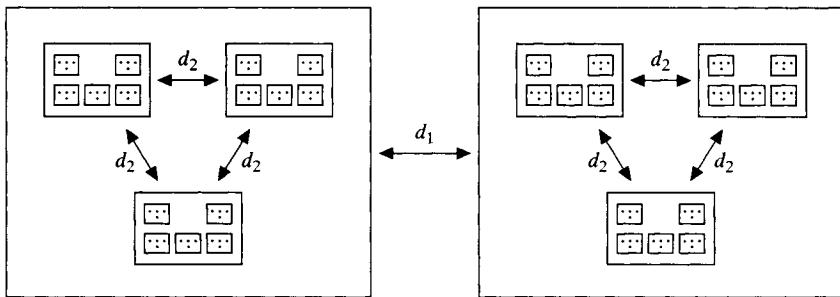
**Proof of (c).** This follows from the

**Monotonicity of basic invariants.** Most natural geometric invariants of mm-spaces are monotone for the Lipschitz order. This applies in particular to the covering number  $\text{Co}(X, \rho, \varepsilon)$ , which is sufficient for (c) via (2).

**Proof of (d) and (e).** This is immediate with the above convergence criterion by the following standard (and obvious) lemma applied to the measures  $\mu_i = \underline{\mu}_r^{X_i}$  on  $M_r \subset \mathbb{R}_+^{r(r-1)/2}$ .

**Monotone convergence lemma:** *Let  $\mu_i$  be a precompact sequence of finite measures on  $\mathbb{R}_+^k$  such that, for every box  $B = [0, t_1] \times [0, t_2] \times \cdots [0, t_k]$  in  $\mathbb{R}^k$ , the numerical sequence  $\mu_i(B)$  is increasing. Then, the  $\mu_i$  converge. Similarly, the  $\mu_i$  converge if  $\mu_i(B)$  are decreasing for all boxes  $B$ .*

**Proof of (f).** Let us describe a class of spaces which bound all precompact subsets in  $\mathcal{X}$ . First, given a (growing) sequence of positive integers  $N_1, N_2, \dots$  and of reals  $d_1, d_2, \dots$  (slowly) converging to zero, we construct a Cantor set  $K = K(N_i, d_i)$  which consists of  $N_1$  equal parts with distances  $d_1$  between the points in different parts; then each part is divided into  $N_2$  pieces with mutual distances  $d_2$ , and so on.

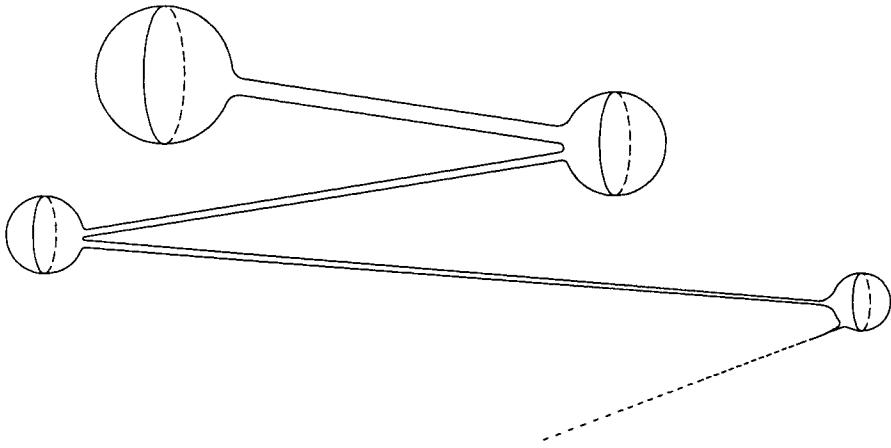


Such  $K$  is given a natural measure, where each of the initial parts have masses  $N_1^{-1}$ , the parts at the second stage have masses  $(N_1 N_2)^{-1}$ , and so on.

Then we take disjoint unions of  $K$ 's, say  $K_1 \sqcup K_2 \sqcup \dots$ , where the measure in  $K_i$  is normalized to have mass  $2^{-i}$  and where the distances between different  $K_i$  are made large. If  $K_j(N_{ij}, d_{ij})$  have fast-growing  $N_{ij}$  and slowly decaying  $d_{ij}$ , then the resulting union is good enough to majorize lots of spaces  $X$ . This implies (f) when all quantifiers are put into place (which we leave for the reader to do).

**3 $\frac{1}{2}$ .16. Lipschitz order in the Riemannian category.** It is obvious that the relation  $X \prec Y$  implies  $\dim X \leq \dim Y$  for (possibly noncompact) Riemannian manifolds of finite mass. In fact, this is also true and obvious for  $m(X) = m(Y) = \infty$  if  $Y$  is *thick*, i.e., if each  $\rho$ -ball in  $Y$  satisfies  $\mu(B(y, \rho)) \geq \kappa(\rho) > 0$  for all  $\rho > 0$ . Yet, there exists a complete Riemannian manifold  $Y$  diffeomorphic to  $\mathbb{R}^2$  which dominates  $\mathbb{R}^n$  for all  $n$ . One can take  $Y$ , for example, obtained by joining a countable union of spheres by very thin, long tubes.

In fact, one can eventually dominate every connected  $X$  of infinite mass using some  $Y$  of this kind. What is more interesting, however, is the possibility of dominating  $X$  by  $\lambda Y$  where  $X$  and  $Y$  are arbitrary compact Riemannian manifolds, possibly with (smooth!) boundaries, which satisfy  $\dim Y \geq \dim X$  and where  $\lambda Y = (Y, \lambda \text{dist}, \lambda^n \mu)$  for the Riemannian distance and measure. So, what we claim is that *there exists  $\lambda = \lambda(X, Y)$  such that  $X \prec \lambda Y$  provided that  $\dim X \leq \dim Y$  and  $X$  is connected*.



**Sketch of the proof.** If  $\dim X = n$  and  $Y$  is diffeomorphic to the  $n$ -ball, we cut  $X^n$  along some piecewise smooth hypersurface and obtain an  $n$ -ball  $B'$  with piecewise smooth boundary. For example,  $S^2$  should be cut along a segment, the 2-torus over a figure eight inside it, etc. Then it is not hard to make a (bi)-Lipschitz homeomorphism  $Y \rightarrow B'$  sending the measure of  $Y$  to a multiple of the  $X$ -measure on  $B'$ .

Next, if  $Y$  is an  $m$ -ball with  $m \geq n$ , then we think of  $Y$  as  $B^n \times B^{m-n}$ , where there is no problem of finding our maps  $B^n \times B^m \rightarrow B^n$ , and then we go from  $Y \simeq B^n \times B^m$  to every compact  $X = X^n$  via  $B^n \rightarrow B' \subset X^n$ .

Finally, every  $Y$  of dimension  $m$  can be 1-Lipschitz mapped onto a Euclidean simplex  $\Delta^m$  preserving the measure. This is done by triangulating  $Y$  into  $m$ -simplices of equal volume and then “folding” across the  $(m-1)$ -dimensional faces. A typical map of this kind goes from the sphere  $S^m = \{x_0^2 + x_1^2 + \dots + x_m^2 = 1\}$  to  $\Delta^m$  by the map  $(x_0, \dots, x_m) \mapsto (x_0^2, x_1^2, \dots, x_m^2)$ . We stop at this point and invite the reader to furnish the details. We also suggest that the reader study the possibility of having the implied map  $Y \rightarrow X$  smooth when  $\dim Y \geq 2 \dim X$  (as the “curved” Archimedes map  $S^2(\pi) \rightarrow [-\pi, \pi] \rightarrow S^1(1)$ ).

**Open questions.** It seems hard to evaluate the *domination constant*  $\lambda = \lambda(X, Y)$  above with *reasonable precision* for specific manifolds  $X$  and  $Y$ . For example, let  $X$  and  $Y$  be the products of round spheres of given radii,  $X = S^{i_1}(r_1) \times S^{i_2}(r_2) \times \dots \times S^{i_k}(r_k)$  and  $Y = S^{j_1}(R_1) \times S^{j_2}(R_2) \times \dots \times S^{j_l}(R_l)$ . What is, roughly,  $\lambda(X, Y)$ ? Or, suppose that  $X$  is a convex hypersurface in  $\mathbb{R}^{n+1}$  with principal curvatures  $\geq 1$ . What is the minimal radius of the round sphere in  $\mathbb{R}^{n+1}$  dominating this  $X$ ? One knows in this regard that there is a 1-Lipschitz diffeomorphism  $f$  of the unit sphere onto  $X$ , but it

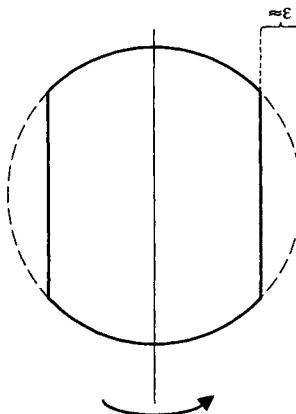
is unclear if one can make such an  $f$  with *constant* Jacobian. A similar question arises when  $X$  has  $\text{Ricci } X \geq n - 1$  and we seek the optimal domination of  $X$  by the round  $n$ -sphere or an  $n$ -ball.

A closely related question is as follows. Suppose we have two equidimensional manifolds  $X$  and  $Y$  which admit a  $\lambda$ -bi-Lipschitz diffeomorphism  $f$  between them, which essentially means that  $d_L(X, Y) \leq \log(\lambda)$ , where  $d_L$  is the Lipschitz distance of 3.1. Then we introduce another distance, say  $d_L^\mu(X, Y)$  corresponding to the best  $\lambda'$  bi-Lipschitz homeomorphism  $f'$  between  $X$  and  $Y$  with *constant* Jacobian. The question is by how much  $\lambda'$  is greater than  $\lambda$  an *generically* (if we only knew what it means!), we expect that the discrepancy between  $\lambda$  and  $\lambda'$  grows exponentially fast with dimension  $n$ , since the jacobian of a map  $f$  can grow as fast at  $(\text{Lip}(f))^n$ . Here are specific examples where we want to evaluate this  $d_L^\mu$ .

- (a) Consider smooth hypersurfaces  $X$  in  $\mathbb{R}^{n+1}$  given by the radial functions  $f$  on the unit sphere  $S^n \subset \mathbb{R}^{n+1}$ , i.e.,

$$X = X_f = \{(s, r) : s \in S^n, r = 1 + f(s)\}$$

in the polar coordinates  $(s, r)$  on  $\mathbb{R}^{n+1}$ . Take all those  $X = X_f$  where the  $C^1$ -norm of  $f$  is  $\leq \varepsilon$ , i.e.,  $|f(s)| \leq \varepsilon$  and  $\|\text{grad } f(x)\| \leq \varepsilon$ . We use here some fixed small  $\varepsilon > 0$ , say  $\varepsilon = 0.1$  and let  $n \rightarrow \infty$ . It is not hard to show that the  $d_L$ -diameter of the space of these  $X$  remains bounded (of order  $\varepsilon$ ), but the  $d_L^\mu$ -diameter grows at least as fast as  $\log(\varepsilon\sqrt{n})$ . A particular hypersurface  $X$  which is about  $(\log\sqrt{n\varepsilon})$ -far from  $S^n$  is obtained as the  $(n - 1)$ -revolution of the curve below (truncated circle).



This  $X$  is distinguished from  $S^n$  by its *observable diameter* (see 3 $\frac{1}{2}$ .20) which equals  $\simeq 1/\sqrt{n}$  for  $S^n$  (see 3 $\frac{1}{2}$ .20) and is  $\simeq \sqrt{\varepsilon}$  for our  $X$  (by

a trivial argument. It is also not hard to bound  $d_L^\mu(X, S^n) \geq \log \sqrt{n\varepsilon}$ . And of course there is much more to this space of surfaces  $X$  (defined by  $\text{dist}_{C^1}(X, S^n) \leq \varepsilon$ ) than our rough(?) lower bound on its diameter.

(b) Consider the convex surfaces  $X$  in  $\mathbb{R}^{n+1}$  with a given pinching of the principal curvatures, say with  $1 \leq \text{curv } X \leq 2$ . Here again the  $d_L$ -diameter remains bounded as  $n \rightarrow \infty$ , but it is unclear what happens to the  $d_L^\mu$ -diameter. Also, a similar problem remains very much open for Riemannian manifolds with (sufficiently) pinched positive sectional curvatures.

(c) Consider all smooth complex hypersurfaces  $X$  of a given degree  $d$  in  $\mathbb{CP}^n$ . We want to understand the following metrics on the space of these  $X$ :

- (i) the metric  $d_L$ ,
- (ii) the metric  $d_L^\mu$ , where one should note that all complex hypersurfaces of a given degree (and dimension) have equal volumes,
- (iii) the *symplectic Lipschitz metric*  $d_L^\omega$ , where we appeal to the *symplectic*  $\lambda$ -Lipschitz maps between our hypersurfaces for the symplectic structure induced by the standard 2-form  $\omega$  on  $\mathbb{CP}^n$ .

Clearly  $d_L \leq d_L^\mu \leq d_L^\omega$ , and one may think that  $d_L^\omega$  is more amenable to computation (at least  $C^1$ -near a fixed  $X_0$ ). But we have only a very vague idea of the global geometry of the space of hyperspaces with any of these three metrics.

Finally, we observe that the Lipschitz order can be directly used to define yet another metric, say  $d_L^\diamond$ , which refers to the minimal  $\lambda$  (or rather  $\log(\lambda)$ ) for which  $X \succ \lambda Y$  and  $Y \succ \lambda X$ . (We suggest that the reader check that this is indeed a metric on the set of isometry classes of compact, equidimensional Riemannian manifolds.) It is interesting to compare  $d_L^\diamond$  with  $d_L^\mu$ , on the one hand, and with  $\square_1$  on the other for specific classes of Riemannian manifolds (e.g., for those with some bound on curvature, injectivity radius, diameter, etc.). And once again, we wish to gain some insight into the geometry of simple(?) spaces (such as in (a), (b), (c) above) with the metric  $d_L^\diamond$  (along with  $d_L^\mu$  and  $\square_1$ , while  $d_L$  and  $d_H$  look interesting only for (c)).

**3½.17. Approximation of mm-spaces by measures in  $(\mathbb{R}^N, \|\cdot\|_{\ell_\infty})$ .** Recall that the  $\ell_\infty$ -norm in  $\mathbb{R}^N$  is given by  $\|b\|_{\ell_\infty} = \sup |b_i|$ ,  $i = 1, \dots, N$ . Thus, every  $N$ -tuple of 1-Lipschitz functions  $\varphi_1, \dots, \varphi_N$  on  $X$  defines a 1-Lipschitz map  $\Phi : X \rightarrow (\mathbb{R}^N, \|\cdot\|_{\ell_\infty})$ . Now, let  $X$  be an mm-space with finite mass, and let  $\varphi_1, \varphi_2, \dots, \varphi_i, \dots$  be a sequence of 1-Lipschitz functions on  $X$  which is  $m_1$ -dense in the space of all 1-Lipschitz functions

$X \rightarrow \mathbb{R}$ . Such a sequence always exists, since the space of functions  $X \rightarrow \mathbb{R}$  is Polish with respect to the metric  $\text{me}_1$  (see 3 $\frac{1}{2}$ .A). We then take  $\Phi_N = (\varphi_1, \varphi_2, \dots, \varphi_N) : X \rightarrow \mathbb{R}^N$  and let  $\underline{X}_N = (\mathbb{R}^N, \mu_N, \|\cdot\|_{\ell_\infty})$ , where  $\underline{\mu}_N$  denotes the  $\Phi_N$ -pushforward of the measure  $\mu$  of  $X$ . Clearly

$$\underline{X}_1 \prec \underline{X}_2 \prec \cdots \prec \underline{X}_N \cdots$$

and

$$\underline{X}_N \xrightarrow{\square_1} X.$$

It follows in particular that there exist maps  $\Psi_N : \underline{X}_N \rightarrow X$  which are 1-Lipschitz up to  $\varepsilon_N \rightarrow 0$  and which almost invert  $\Phi_N$  (compare (3' $_b$ )).

## E. Concentration phenomenon

**3 $\frac{1}{2}$ .18. Linear geometry of  $S^n$ .** We start with several examples of geometric behavior of measures on  $n$ -dimensional spaces where interesting patterns develop for large  $n$ .

(a) Consider the unit Euclidean ball  $B^n \subset \mathbb{R}^n$  and observe that most of its measure is contained in the  $\varepsilon$ -neighborhood of the boundary. In fact, the proportion of the measure lying outside  $U_\varepsilon(\partial B^n)$  equals  $(j - \varepsilon)^n$  which is small for large  $\varepsilon/n$ . In fact, if  $\varepsilon \sim \lambda/n$ , then  $(1 - \varepsilon)^n \sim e^{-\lambda}$ . This implies the following bound on the  $d_{1,1}$ -distance between the normalized measures  $\mu = \mu_{B^n}$  and  $\mu' = \mu_{S^n}$  on  $B^n$ ,

$$d_{1,1}(\mu, \mu') \leq (\log(n))/n.$$

**Question:** Is the  $\square_1$ -distance between  $B^n$  and  $S^{n-1}$  realized by the standard embedding  $S^{n-1} \rightarrow \partial B^n \subset B^n$ , or equivalently by the radial projection  $\varphi : B^n \rightarrow S^{n-1}$ ?

(b) An equatorial sphere  $S^{n-1} \subset S^n$  contains most of the measure of  $S^n$  in its  $\varepsilon$ -neighborhood  $U_\varepsilon(S^{n-1})$ . In fact, most of the measure of  $S^n$  is, roughly,  $(1/\sqrt{n})$ -close to  $S^{n-1}$ . To see this, observe that the distance function  $d(x) = \text{dist}(x_0, x) - \pi/2$  on  $S^n$  pushes forward the spherical measure to the segment  $[-\pi/2, \pi/2]$  with the density  $\gamma_n(\cos(t))^{n-1}$ . Thus, the complementary measure  $\mu(S^n \setminus U_\varepsilon(S^{n-1}))$  comes from the contribution to the integral

$$\int_{-\pi/2}^{\pi/2} (\cos t)^{n-1} dt$$

from the points in  $[-\pi/2, \pi/2] \setminus [-\varepsilon, \varepsilon]$ . This is denoted

$$\kappa_n = \kappa_n(\varepsilon) = \frac{\int_{-\varepsilon}^{\pi/2} (\cos t)^{n-1} dt}{\int_0^{\pi/2} (\cos t)^{n-1} dt}$$

and satisfies

$$\kappa_n(\varepsilon) < 2e^{-(n-1)\varepsilon^2/2}$$

(which is  $O(1)$  for  $\varepsilon \simeq 1/\sqrt{n}$ ), where the bound on  $\kappa_n$  is derived from:

- (i) the inequality  $\cos t < e^{-t^2/2}$  for  $t \in [-\pi/2, \pi/2]$ ,  $t \neq 0$ , following from the Taylor expansions

$$\cos t = \sum_i (-1)^i t^{2i} / (2i)! \quad \text{and} \quad e^{-t^2/2} = \sum_i (-1)^i t^{2i} / i! 2^i;$$

- (ii) the relations

$$\int_{-\varepsilon}^{\pi/2} (e^{-t^2/2})^n dt = \int_{\varepsilon\sqrt{n}}^{\sqrt{n}\pi/2} e^{-s^2/2} ds / \sqrt{n},$$

and

$$\begin{aligned} \int_a^b e^{-s^2/2} ds &\leq e^{-a^2/2} \int_0^{b-a} e^{-s^2/2} ds \\ &\leq e^{-a^2/2} \int_0^\infty e^{-s^2/2} ds \\ &= \sqrt{\pi/2} e^{-a^2/2} \\ &\leq 2e^{-a^2/2}, \end{aligned}$$

for  $0 \leq a \leq b$ .

- (iii) the estimate

$$\int_0^{\pi/2} (\cos t)^n dt \geq 1/\sqrt{n}$$

(see §2 in [Mil–Sch] for details).

**Exercise:** Evaluate the distance  $\underline{\square}_1(S^n, S^{n-1})$  and, more generally, the distance  $\underline{\square}_1(S^n, S^m)$ . Observe that the sequence of unit spheres  $S^n$  with normalized Riemannian measures *does not*  $\underline{\square}_1$ -converge for  $n \rightarrow \infty$ , nor does it admit a convergent subsequence.

The concentration of the mass of  $S^n$  near  $S^{n-1}$  implies that most pairs of points  $x_1, x_2 \in S^n$  have  $\text{dist}_{S^n}(x_1, x_2)$  close to  $\pi/2$  for large  $n$  (and  $\text{dist}_{\mathbb{R}^{n+1}}(x_1, x_2)$  close to  $\sqrt{2}$ ). This brings us to the following concept.

**Characteristic size of  $X$ .** This terminology applies to an  $X$  where the distance function  $\text{dist} : X \times X \rightarrow \mathbb{R}$  is  $\text{me}_1$ -close to a constant function, say  $d_0$ , and  $d_0$  is called the (*approximate*) *characteristic size* of  $X$ . To be precise, we have to indicate an  $\varepsilon$  such that  $\text{me}_1(\text{dist}, d_0) \leq \varepsilon$  or to apply the notion of the characteristic size to a sequence of spaces  $X^n$ ,  $n = 1, 2, \dots$ , where  $\text{me}_1(\text{dist}_{X^n}, d_0) \rightarrow 0$  for  $n \rightarrow \infty$ . Notice that the existence of this (asymptotic) characteristic size  $d_0$  for  $X^n$  implies that the average diameters of the  $X^n$  also converge to  $d_0$  and that the  $M_r$ -valued pairwise distance function  $K_r$  on  $X \times \dots \times X$  ( $r$  factors)  $\text{me}_1$  converges to the constant matrix  $M_{d_0}$  with all off-diagonal entries equal to  $d_0$ . In other words, each measure  $\mu_r^{X^n}$  converges to a single atom of mass equal to  $(\lim_{n \rightarrow \infty} \mu(X))^r$  situated at  $M_{d_0} \in M_r$ .

**3½.19.** Coming back to  $S^n$  and  $B^n$  we can say that these have characteristic sizes about  $\mu/2$  and  $\sqrt{2}$  respectively for large  $n \rightarrow \infty$ . However, the following striking theorem shows that  $S^n$  (and consequently  $B^n$ ) converges, in some sense, to a single point since every 1 Lipschitz function on  $S^n$  for large  $n$  becomes  $\text{me}_1$ -close to a constant.

**Levy concentration theorem:** *An arbitrary 1-Lipschitz function  $f$  on  $S^n$  concentrates near a single value  $a_0 \in \mathbb{R}$  as strongly as the distance function does. Namely,*

$$\mu\{x \in S^n : |f(x) - a_0| \geq \varepsilon\} < \kappa_n(\varepsilon) \leq 2e^{-(n-1)\varepsilon^2/2}, \quad (*)$$

where  $\mu$  refers to the normalized spherical measure, and  $\kappa_n$  is the above

$$\kappa_n(\varepsilon) = \frac{\int_{-\varepsilon}^{\pi/2} (\cos t)^{n-1} dt}{\int_0^{\pi/2} (\cos t)^{n-1} dt}.$$

**Remarks on the average and Levy mean.** The specific value  $a_0$  which makes  $(*)$  sharp is the so-called *Levy mean* of  $f$ , and has the property that the level set  $f^{-1}(a_0) \subset S^n$  divides the sphere into *equal halves*. More rigorously, this  $a_0$  is uniquely characterized by the inequalities

$$\mu(f^{-1}(-\infty, a_0]) \geq \frac{1}{2} \quad \text{and} \quad \mu(f^{-1}[a_0, \infty)) \geq \frac{1}{2},$$

(where we should keep in mind the possibility of  $\mu(f^{-1}(a_0)) > 0$ ). And we would not lose much by using the ordinary *mean*, i.e., *the average*  $m^{-1} \int_X f(x) dx$  for  $m = \mu(X)$  (which equals one for our normalized  $\mu_{S^n}$ ). Namely, if a function concentrates near some value  $a_0$ , then this  $a_0$  must be close to the average  $a$  of  $f$ . In fact,  $(*)$  obviously implies that

$$\mu\{x \in S^n : |f(x) - a| \geq 2\varepsilon + \pi\kappa_n\} \leq \kappa_n \quad (\circ)$$

(compare ObsCRad in 3 $\frac{1}{2}$ .31).

The Levy mean of a function  $f$  on an arbitrary measure space  $(X, \mu)$  with  $\mu(X) < \infty$  can be adequately expressed entirely in terms of the push-forward measure  $\mu_* = f_*(\mu)$  on  $\mathbb{R}$ . Namely, the Levy mean equals the  $a_0 \in \mathbb{R}$  such that

$$\mu_*(-\infty, a_0] \geq \frac{1}{2}\mu_*(\mathbb{R}) \quad \text{and} \quad \mu_*[a_0, \infty) \geq \frac{1}{2}\mu_*(\mathbb{R}).$$

In fact, the concentration property of  $f$  claimed by Levy's theorem amounts to the concentration of  $\mu_*$  in the  $\varepsilon$ -interval around  $a_0$ ,

$$\mu_*\{y \in \mathbb{R} : |y - a_0| \geq \varepsilon\} \leq \kappa_n \leq e^{-(n-1)\varepsilon^2/2}.$$

**On the uniqueness of the Levy mean.** If the measure  $\mu_* = f_*(\mu)$  in  $\mathbb{R}$  has disconnected support, then the Levy mean may be non unique. In fact, the values  $a \in \mathbb{R}$  dividing  $\mu$  into equal halves may range over some interval in  $\mathbb{R}$ . If this is the case, we *define* the Levy mean to be the *center* of this interval.

**Idea of the proof.** Fix two positive numbers  $\mu_0 \leq 1$  and  $\varepsilon$ . Consider subsets  $X \subset S^n$  with  $\mu(X) = \mu_0$  and minimize  $\mu(U_\varepsilon(X))$  over all such  $X$ , where  $U_\varepsilon(X)$  denotes the  $\varepsilon$ -neighborhood of  $X$ . The *spherical isoperimetric inequality* (easily) implies that the minimum is achieved by some ball  $B(r) \subset S^n$  (spherical cap), namely the one which has  $\mu(B(r)) = \mu_0$ .

Now we return to our  $f$  on  $S^n$  and consider the level  $\Sigma = f^{-1}(a_0) \subset S^n$  for the Levy mean  $a_0$  of  $f$ . The discussion above shows that

$$\mu(U_\varepsilon(\Sigma)) \geq \mu(U_\varepsilon(S^{n-1}))$$

for all  $\varepsilon > 0$  and since  $f$  is 1-Lipschitz, all of  $U_\varepsilon(\Sigma = f^{-1}(a_0))$  goes to the segment  $[a_0 - \varepsilon, a_0 + \varepsilon]$ .

(Notice that the only technically nontrivial ingredient of this proof is the isoperimetric inequality, which claims that *among all domains in  $S^n$  with a given volume, the minimal volume of the boundary is assumed by some ball in  $S^n$* .)

**3 $\frac{1}{2}$ .20. Observable diameter.**  $\text{ObsDiam}_Y(X) = \text{diam}(X \xrightarrow{\text{Lip}_1} Y, m - \kappa)$ . We start by defining the (partial) diameter  $\text{diam}(\nu, m - \kappa)$  for a measure  $\nu$  on a metric space  $Y$  as the infimal  $D$  such that  $Y$  contains a subset  $Y_0$  of diameter  $\text{diam}(Y_0) \leq D$  and measure  $\nu(Y_0) \geq m - \kappa$ , where  $m$  stands for the total mass  $\nu(Y)$ . Clearly, this diameter is monotone for the *Lipschitz*

*ordering:* if  $\nu = f_*(\mu)$  for a 1-Lipschitz map  $f: X \rightarrow Y$ , then  $\text{diam}(\nu, m - \kappa) \leq \text{diam}(\mu, m - \kappa)$  for all  $\kappa$ . What is not obvious at all is that this diameter may dramatically decrease under all 1-Lipschitz maps  $f$  from  $X$  to certain  $Y$ , such as  $Y = \mathbb{R}$  for instance. We define, keeping this in mind, the *observable diameter*  $\text{diam}(X \xrightarrow{\text{Lip}_1} Y, m - \kappa)$  as the infimal  $D$  such that the measure  $\mu_* = f_*(\mu)$  on  $Y$  has  $\text{diam}(\mu_*, m - \kappa) \leq D$  for all 1-Lipschitz maps  $f: X \rightarrow Y$ . Here, we think of  $\mu$  as a *state* on the configuration space  $X$ , and  $f$  is interpreted as an *observable*, i.e., an observation device giving us the visual (tomographic) image  $\mu_*$  on  $Y$ .

We watch  $\mu_*$  in  $Y$  with a naked eye which has certain sensitivity  $\sigma$  and which cannot distinguish a part of  $Y$  of measure (luminicity) less than  $\kappa$  for  $\sigma\kappa \ll 1$ . (Of course, we could use an observable  $f$  with a higher resolution  $\lambda = \text{Lip}(f)$ , but this can be achieved by just scaling  $Y \mapsto \lambda^{-1}Y \stackrel{\text{def}}{=} (Y, \lambda^{-1}\text{dist}_Y)$ , so we can stick to  $\lambda = 1$  without losing the freedom of notation.) The observable diameter is usually rather unsensitive to  $\kappa$  when  $\kappa$  is small, and we may pretend that  $\kappa$  is a certain given small number, say  $\kappa = 10^{-10}$ . Then we abbreviate  $\text{diam}(X \xrightarrow{\text{Lip}_1} Y, m - \kappa)$  with  $\text{ObsDiam}_Y(X) = \text{ObsDiam}_Y(X, -\kappa)$  and write  $\text{ObsDiam}(X)$  for  $\text{ObsDiam}_{\mathbb{R}}(X)$ . Now, the Levy inequality (\*) can be loosely stated as

$$\text{ObsDiam}(S^n) = O(1/\sqrt{n})$$

(and, in fact,  $\text{ObsDiam}(S^n) \simeq 1/\sqrt{n}$  since the inequality (\*) becomes an equality for the distance function  $f(x) = \text{dist}(x_0, x)$  on  $S^n$ ). More explicitly, (\*) implies that

$$\text{diam}(S^n \xrightarrow{\text{Lip}_1} \mathbb{R}, 1 - \kappa) \leq \frac{2\sqrt{2}}{\sqrt{n-1}} \sqrt{-\log(\kappa/2)} \approx \frac{1}{\sqrt{n}} \sqrt{-\log \kappa}. \quad (*)$$

This should be compared with our earlier evaluation of the characteristic size and/or the average diameter of  $S^n$ , which both converge to  $\pi/2$  as  $n \rightarrow \infty$ .

**3½.21. Spheres, cubes, and the law of large numbers.** The concentration phenomenon generalizes the *law of large numbers*, where  $X^n$  is the cartesian power of a given space  $X$ , e.g., the  $n$ -cube  $[0, 1]^n$ , and then the relevant observable function is the averaged sum of the  $n$  coordinate projections  $[0, 1]^n \rightarrow [0, 1]$ , namely  $(1/n) \sum_{i=1}^n t_i$ , which concentrates near the single value  $1/2$ . In geometric language, this says that the normal projection of the cube  $[0, 1]^n$  to the principal diagonal identified with the segment  $[0, \sqrt{n}]$  sends most of (the measure of) the cube to the subsegment

$$[\sqrt{n}/2 - \varepsilon\sqrt{n}/2, \sqrt{n}/2 + \varepsilon\sqrt{n}/2] \subset [0, \sqrt{n}]$$

with small  $\varepsilon$ . In fact, much of the pushforward measure  $\mu_*$  is concentrated in the segment  $[\sqrt{n}/2 - c, \sqrt{n}/2 + c]$  for some (large)  $c$  independent of  $n$ , as follows from the central limit theorem. In other words ,

$$\text{diam}(\mu_*, 1 - \kappa) \leq C(\kappa)$$

when  $\kappa > 0$ , where  $C$  is some positive function.

We will generalize this later on to all Lipschitz functions  $f$  on  $[0, 1]^n$ , thus showing that

$$\text{diam}([0, 1]^n \xrightarrow{\text{Lip}_1} \mathbb{R}, 1 - \kappa) \leq C(\kappa).$$

This is similar to the behavior of the  $(n - 1)$ -sphere of radius  $\sqrt{n}$ , which has according to  $(*)$

$$\text{diam}(S^{n-1}(\sqrt{n}) \xrightarrow{\text{Lip}_1} \mathbb{R}, 1 - \kappa) \simeq \sqrt{-\log(\kappa)}$$

for  $n \rightarrow \infty$ . Actually, this sphere

$$S^{n-1}(\sqrt{n}) = \{x_1, x_2, \dots, x_n : \sum_{i=1}^n x_i^2 = n\}$$

is quite similar to the unit cube in many respects. For example, the two have comparable volume, since  $\text{vol } S^{n-1}(\sqrt{n}) \approx \text{const}^n$ , which is like the volume of the scaled cube  $[0, \text{const}]^n$  (while the *unit* sphere has much smaller volume, something of order  $n^{-n/2}$ ). We also know that the average diameter of  $S^{n-1}(\sqrt{n})$  (and the characteristic size as well) is about  $\sqrt{n}$  (more precisely, it is  $\sim \pi\sqrt{n}/2$  for  $n \rightarrow \infty$ ), and now we shall see that the same is true for the  $n$ -cube. Actually, it is much easier to integrate  $(\text{dist}(x, y))^2$  over  $[0, 1]^n \times [0, 1]^n$  rather than  $\text{dist}(x, y)$  itself. The former integrates as follows

$$\begin{aligned} \int \int_{[0, 1]^{2n}} \text{dist}^2(x, y) dx dy &= \int \int_{[0, 1]^{2n}} \sum_{i=1}^n (x_i - y_i)^2 \\ &= n \int_0^1 \int_0^1 (t - s)^2 dt ds \\ &= n/3. \end{aligned}$$

On the other hand,  $\sup \text{dist}(x, y) = \sqrt{n}$ , and so,

$$\sqrt{n} \geq \int \int_{[0, 1]^{2n}} \text{dist}(x, y) dx dy \geq \frac{\sqrt{n}}{3}.$$

Then, by the concentration in  $[0, 1]^n$  mentioned above, the characteristic size of  $[0, 1]^n$  is also about  $\sqrt{n}$ .

**Question:** What is the  $\square_\lambda$ -distance between  $[0, 1]^n$  and  $S^n(R)$  for given  $R$ ? (where we refer to the *normalized* measure in  $S^n$ )? What are possible Lipschitz maximizations of  $S^n(R)$  by  $[0, 1]^n$  and vice-versa (where it may be reasonable to replace  $S^n$  by the ball  $B^n$ )? (See 3 $\frac{1}{2}$ .59 for a continuation of this discussion, in which an appropriate distance between  $[0, 1]^n$  and  $S^n(\sqrt{n})$  is estimated as  $\log \log(n)$ .)

**3 $\frac{1}{2}$ .22. The Maxwell–Boltzmann distribution.** We can look at the sphere  $S^{3n-1}(\sqrt{n}) \subset \mathbb{R}^{3n} = (\mathbb{R}^3)^n$  as the constant (kinetic) energy surface in the (velocity) space of the system of  $n$  (noninteracting) particles in (a box in)  $\mathbb{R}^3$ , where the sphere equation  $\sum_{i=1}^n \|x_i\|^2 = n$  for  $x_i \in \mathbb{R}^3$  says that the *energy per particle* equals one independently of  $n$ . A man/woman in the street observation consists in measuring the pressure exerted by the particles on one of the walls of the box, which roughly amounts to projecting the velocity vectors of the particles to the normal direction to the wall and then summing up the squares of the positive (i.e., directed towards the wall) projections. A more general (macroscopic) observable associated with a domain  $\Omega$  in the (velocities) space  $\mathbb{R}^3$  is given by the number  $N(\Omega)$  of particles (whose velocity vectors are) contained in  $\Omega$ . Actually, one measures instead the average  $N(\Omega)/n$ ; furthermore, one may consider some function  $\varphi: \mathbb{R}^3 \rightarrow \mathbb{R}$  and take the average  $(1/n) \sum_{i=1}^n \varphi(x_i)$ , where  $x_i \in \mathbb{R}^3$  denotes the (velocity of the)  $i$ -th particle, i.e., the  $i$ -th component of  $x = (x_1, \dots, x_n) \in S^{3n-1}(\sqrt{n})$ . Notice that if  $\varphi$  is a  $\lambda$ -Lipschitz function on  $\mathbb{R}^3$ , then  $\Phi(x) = \Phi(x_1, \dots, x_n)$  is  $(\lambda/\sqrt{n})$ -Lipschitz on  $\mathbb{R}^{3n}$  and, in particular, on  $S^{3n-1}(\sqrt{n}) \subset \mathbb{R}^{3n}$ . Thus, it becomes  $\lambda$ -Lipschitz as we scale  $S^{3n-1}(\sqrt{n})$  to the unit sphere  $S^{3n-1} = S^{3n}(1)$ . It follows from Levy's theorem, and was known to Maxwell long before Levy, that for most points  $x \in S^{3n-1}(\sqrt{n})$ , the value  $\Phi(x)$  is very close to the average of  $\Phi(x)$  over  $x \in S^{3n-1}(\sqrt{n})$ . This average obviously equals the integral of  $\varphi$  by the measure  $\mu_*$  on  $\mathbb{R}^3$  which is the pushforward of the normalized spherical measure on  $S^{3n-1}(\sqrt{n}) \subset (\mathbb{R}^3)^n$  under the projection  $x = (x_1, x_2, \dots, x_n) \mapsto x_1$ . Now, this measure is given by the density function

$$C_n(\sqrt{1 - \|x_1\|^2/n})^{3n-4} dx_1$$

on  $\mathbb{R}^3$ , which converges as  $n \rightarrow \infty$  to the Gaussian measure with density

$$Ce^{-3\|x_1\|^2/2} dx_1$$

where the (normalization) constant  $C$  equals

$$\left( \int_{\mathbb{R}^3} e^{-3\|x_1\|^2/2} dx_1 \right)^{-1} = \left( \frac{2\pi}{3} \right)^{-1/2}.$$

The asymptotic formula  $\mu_* \simeq Ce^{-3\|x_1\|^2/2}$  is known under the name of the *Maxwell (-Boltzmann) distribution law*. It gives a fairly sharp quantitative estimate of concentration of the measure of  $S^{3n-1}$  near its equator of codimension 3, but, apparently it tells us precious little about the actual (not the averaged!) distribution of the coordinates (particles)  $x_1, \dots, x_n$  in  $\mathbb{R}^3$  of an individual configuration  $x = (x_1, x_2, \dots, x_n) \in S^{3n-1}(\sqrt{n})$ . Yet, by the Levy (-Maxwell) theorem, the distribution of the points  $x_1, \dots, x_n$  in  $\mathbb{R}^n$  closely follows  $Ce^{-3\|x\|^2/2}$  for most  $x \in S^{3n-1}(\sqrt{n})$ . Namely, the average of the atomic measures concentrated at  $x_i$ , denoted  $(1/n) \sum_{i=1}^n \delta(x_i)$  stays  $di_1$ -close to the Gaussian measure with the density  $Ce^{-3\|x\|^2/2}$  for most points  $x \in S^{3n-1}(\sqrt{n})$ . Here, we think of  $x \mapsto (1/n) \sum_{i=1}^n \delta(x_i)$  as a map  $f_n$  from  $S^{3n-1}(\sqrt{n})$  to the space  $M$  of probability measures on  $\mathbb{R}^3$  with the metric  $di_1$  and claim that these  $f_n: S^{3n-1}(\sqrt{n}) \rightarrow M$  concentrate to the constant map sending the sphere to the Gaussian measure. (We shall discuss on several occasions the concentration of maps  $X \rightarrow Y$  for general  $Y$ , see, e.g., 3 $\frac{1}{2}$ .41.)

The above is similar to the *law of large numbers for mm spaces*  $X$ , where we look at the map  $f_n$  from  $X^n = X \times X \times \dots \times X$  ( $n$  factors) to the space  $P = P(X)$  of probability measures on  $X$  which assigns the measure  $(1/n) \sum_{i=1}^n \delta(x_i)$  to each  $(x_1, \dots, x_n) \in X^n$ . The law of large numbers claims that the concentration of  $f_n$  for large  $n$  to the constant map sending most of  $X^n$  to the normalized measure  $\mu/\mu(X)$  on  $X$ . Moreover, if  $\mu$  is normalized, (i.e.,  $\mu(X) = 1$ ), one has the *strong law of large numbers*. This applies to the infinite product  $X^\infty = (X, \mu) \times (X, \mu) \times \dots$  and claims that the sequence of measures  $f_n(\bar{x}) = (1/n) \sum_{i=1}^n \delta(x_i)$  on  $X$ , with  $\bar{x}$  standing for  $(x_1, x_2, \dots, x_n, \dots) \in X^\infty$ , converges for almost all  $\bar{x} \in X^\infty$  to the original measure  $\mu \in P(X)$ . (This trivially follows, for example, from the individual ergodic theorem applied to the shift  $(x_1, x_2, x_3, \dots) \mapsto (x_2, x_3, \dots)$  on  $X^\infty$ .) In other words, almost every sequence  $x_1, x_2, \dots$  is *uniformly distributed* on  $X$ . Consequently, every mm-space of finite mass admits a uniformly distributed sequence of points (see [Ellis]).

**3 $\frac{1}{2}$ .23. Normal law à la Levy.** The projection of  $S^n(\sqrt{n})$  to  $\mathbb{R}$  pushes forward the normalized measure  $\mu$  on  $S^n(\sqrt{n})$  to some measures  $\mu_n$  which converge as  $n \rightarrow \infty$  to the Gaussian measure  $\nu = Ce^{-x^2/2} dx$  on  $\mathbb{R}$  for  $C = (2\pi)^{-1/2}$  by the Maxwell-Boltzmann theorem. And Levy's theorem (or rather the underlying spherical isoperimetric inequality) implies that *this  $\nu$  majorizes every measure  $\nu'$  on  $\mathbb{R}$  which appears as a limit of pushforwards of  $\mu$  under 1-Lipschitz maps  $f_n: S^n(\sqrt{n}) \rightarrow \mathbb{R}$* . Namely, if  $x$  and  $x'$  are points in  $\mathbb{R}$  such that  $\nu(-\infty, x] \leq \nu'(-\infty, x']$  and  $\nu[x, \infty] \leq \nu'[x', \infty]$  (we

could have said  $\nu(-\infty, x] = \nu'(-\infty, x']$  if we knew that  $x'$  was not an atom for  $\nu'$ ), then the density of  $\nu'$  at  $x'$  is greater than  $Ce^{-x'^2/2}$ . It follows that *there exists a unique monotone increasing 1-Lipschitz map  $\alpha: \mathbb{R} \rightarrow \mathbb{R}$  pushing forward  $\nu$  to  $\nu'$ .*

Now, we turn to 1-Lipschitz maps  $f_n: S^n(\sqrt{n}) \rightarrow \mathbb{R}^k$  for a given  $k \geq 2$  and look at the measures  $\nu'$  arising as limits of  $(f_n)_*(\mu)$  on  $\mathbb{R}^k$ . There is a distinguished measure among these  $\nu'$ , namely the Gaussian  $\nu = C_k e^{-\|x\|^2/2} dx$  for  $C_k = (2\pi)^{-k/2}$ . One may expect that this  $\nu$  majorizes all  $\nu'$  in a reasonable way, i.e., there exists a “nice” (1-Lipschitz?) map  $\alpha: \mathbb{R}^k \rightarrow \mathbb{R}^k$  with  $\alpha_*(\nu) = \nu'$  for all  $\nu'$ .

Observe that *all measures  $\nu'$  above obviously satisfy the isoperimetric inequality induced by that in  $S^n(\sqrt{n})$  for  $n \rightarrow \infty$ .* Namely, if  $\Omega$  is an arbitrary domain and  $B \subset \mathbb{R}^k$  is a halfspace such that  $\nu(B) = \nu'(\Omega)$ , then *the  $\nu'$ -measure of the  $\varepsilon$ -neighborhood of the boundary  $\partial\Omega$  of  $\Omega$  is bounded from below by the  $\nu$  measure of such a neighborhood of  $\partial B$ , i.e.,  $\nu'(U_\varepsilon(\partial\Omega)) > \nu(U_\varepsilon(\partial B))$  for all  $\varepsilon \geq 0$ .*

Actually, this result is quite nontrivial for the Gaussian measure  $\nu$  itself, i.e., for  $\nu' = \nu$ , where it is highly appreciated by the probability people and is called *the Gaussian isoperimetric inequality* (see [Tal]NII and the references therein).

**Exercise:** Identify the extremal domains  $\Omega$  and measures  $\nu'$  where

$$\lim_{\varepsilon \rightarrow 0} \nu'(U_\varepsilon(\partial\Omega))/\nu(U_\varepsilon(\partial B)) \rightarrow 1$$

by adopting the concavity argument from 3 $\frac{1}{2}$ .27.

One could replace the spheres  $S^n(\sqrt{n})$  above by another natural sequence of mm spaces  $X^n$  with  $\text{ObsDiam}(X^n) = O(1)$  for  $n \rightarrow \infty$  and try to characterize the (space of) limits of the pushforward measures  $\nu'$  under 1-Lipschitz maps  $X^n \rightarrow \mathbb{R}^k$ . However, I doubt that even the case  $X^n = [0, 1]^n$  has been thoroughly investigated, not to mention many other sequences, such as  $\sqrt{n}\mathbb{C}P^n$ ,  $\sqrt{n}\mathbb{H}P^n$ ,  $S^{n_1}(\sqrt{n_1}) \times S^{n_2}(\sqrt{n_2}) \times \cdots \times S^{n_m}(\sqrt{n_m})$ ,  $\ell_p$ -products, etc., which we shall meet in the following sections. Sometimes one may try the first eigenfunction (or a combination of these) of the Laplace operator on  $X^n$  instead of the linear projection  $S^n \rightarrow \mathbb{R}$  in order to generate the corresponding “normal law.”

**3 $\frac{1}{2}$ .24. Approximating the spherical means on  $S^n(\sqrt{n})$  by the Gaussian  $C_{n+1}e^{-\|x\|^2/2} dx$ .** The Gaussian density is constant on the concentric spheres in  $\mathbb{R}^{n+1}$  and equals  $C'R^n e^{R^2/2} dR ds$  in polar coordinates. The density function  $R^n e^{-R^2/2}$  achieves its maximum at  $R = \sqrt{n}$  and is rather sharply concentrated near this  $R = \sqrt{n}$ . Namely, the measure

outside the segment  $[\sqrt{n} - r, \sqrt{n} + r]$  has mass  $\leq 2e^{-r^2/2}$ . This follows trivially from the Gaussian isoperimetric inequality above or can be shown by a direct, elementary computation appealing to the strict log-concavity of  $R^n e^{R^2/2}$ , i.e., to the inequality  $(\log R^n e^{-R^2/2})'' \leq -1$ . Thus, almost all the mass of the Gaussian measure  $C_{n+1} e^{-\|x\|^2/2}$  is located near the sphere  $S^n(\sqrt{n}) \subset \mathbb{R}^{n+1}$ . In fact, the Gaussian measure outside the  $r$ -neighborhood  $A_r(\sqrt{n})$  of this sphere is  $\leq 2e^{-r^2/2}$ .

**Exercise:** Majorize the sphere by the above  $r$ -neighborhood  $A_r(\sqrt{n})$  with Gauss measure via the normal (radial) projection  $A_r(\sqrt{n}) \rightarrow S^n(\sqrt{n} - r)$  and thus derive the spherical isoperimetric inequality (with an almost sharp constant) from the (sharp!) Gaussian one (mentioned earlier).

Notice that the Gauss measure  $C_{n+1} e^{-\|x\|^2/2} dx$  equals the product of  $n+1$  copies of  $e^{-x^2/2} dx$  on  $\mathbb{R}$ . Thus, the spherical measure may be seen as an approximate product measure which makes the similarity between  $S^n(\sqrt{n})$  and  $[0, 1]^n$  less surprising (compare Appendix V in [Mil–Sch]).

**3 $\frac{1}{2}$ .25. Canonical and microcanonical.** The above illustrates the physical idea of the *equivalence between the canonical and microcanonical measures* in statistical mechanics which applies to certain (physically meaningful) functions: “energies”  $E(x) = E_n(x)$  on  $\mathbb{R}^n$ . Recall that one introduces the *microcanonical measure*  $\mu_{\text{mic}} = \mu_{\text{mic}}(\rho)$  supported on the energy surface

$$S(\rho) = \{x \in \mathbb{R}^n : E(x) = \rho\}$$

by first restricting the Lebesgue measure  $\mu$  to the “annuli”

$$S_r(\rho) = \{x \in \mathbb{R}^{n+1} : \rho - r \leq E(x) \leq \rho + r\},$$

then by normalizing this  $\mu|_{S_r(\rho)}$  and by finally letting  $r \rightarrow 0$ . Actually, one does not need  $r \rightarrow 0$  but rather  $r/\rho \rightarrow 0$  as  $n \rightarrow \infty$ . In fact, one typically has  $\rho = \rho_n \simeq n$  for  $n \rightarrow \infty$ , i.e., having bounded energy per particle, while  $r = r_n = o(n)$ .

Next, one introduces the *canonical measure*  $\mu_{\text{ca}} = \mu_{\text{ca}}(\beta)$  with the normalized density  $e^{-\beta E(x)}$ ,

$$\mu_{\text{ca}} = \text{const } e^{-\beta E(x)} \mu,$$

where  $\mu = dx$  is Lebesgue measure and

$$\text{const} = \mu(e^{-\beta E(x)})^{-1} = \left( \int_{\mathbb{R}^n} e^{-\beta E(x)} dx \right)^{-1}.$$

The above-mentioned equivalence  $\mu_{\text{ca}} \sim \mu_{\text{mic}}$  refers to a certain correspondence  $\rho \mapsto \beta = \beta(\rho)$  so that the canonical measure  $\mu_{\text{ca}}(\beta)$  remains rather

close to  $\mu_{\text{mic}}(\rho)$  for suitable  $\rho = \rho_n$ ,  $\beta = \beta(\rho_n)$  and  $n \rightarrow \infty$ . This closeness can be expressed in terms of our metrics  $\text{di}_\lambda$ ,  $\text{Tra}_\lambda$ , and/or  $\text{Lid}_b$ , or, more generally, in terms of

$$|\mu_{\text{ca}}(\Phi) - \mu_{\text{mic}}(\Phi)|$$

for a suitable class of functions (observables)  $\Phi$  on  $\mathbb{R}^n$ . In particular, we can insist that the  $E$ -pushforwards of  $\mu_{\text{ca}}$  and  $\mu_{\text{mic}}$  be mutually close in  $\mathbb{R}$ . Since  $\mu_{\text{mic}}(\rho)$  goes to the  $\delta$ -measure  $\delta(\rho)$  on  $\mathbb{R}$ , this amounts to a sufficient concentration of  $\underline{\mu}_{\text{ca}} = E_*(\mu_{\text{ca}})$  near  $\rho = \rho_n$  for  $\beta = \beta_n = \beta(\rho_n)$ . In other words, the  $\underline{\mu}_{\text{ca}}$ -measure of the segment  $[\rho - r, \rho + r]$  must be close to one for relatively small  $r$  (e.g.,  $\rho = n$  and  $r = o(n)$ ).

Here is the common physicists' recipe for determining  $\beta = \beta(\rho)$ . Let  $\underline{\mu} = E_*(\mu)$  be the pushforward of the Lebesgue measure of  $\mathbb{R}^n$ , and write

$$\underline{\mu}_{\text{ca}} = C e^{-\beta\rho} \underline{\mu} = \varphi(\rho) e^{-\beta\rho} d\rho$$

for the constant

$$C = C_\beta = \left( \mu(e^{-\beta E(x)}) \right)^{-1} = (\underline{\mu}(e^{-\beta\rho}))^{-1},$$

and the density function  $\varphi$  of the measure  $C\underline{\mu}$ . We choose  $\beta$  by requiring that the derivative of the function  $\psi(\rho) = \psi_\beta(\rho) = \varphi(\rho)e^{-\beta\rho}$  vanishes at given  $\rho = \rho_n$  (hoping that this is a maximum of  $\psi(\rho)$  with sharp drop of  $\psi$  away from this  $\rho = \rho_n$ ). Thus,

$$\psi'_\beta = \varphi'(\rho) e^{-\beta\rho} - \beta \varphi(\rho) e^{-\beta\rho} = 0,$$

and so

$$\beta = \beta(\rho) = (\log \varphi(\rho))'.$$

Everything here works fine if  $\varphi$  is smooth and  $(\log \varphi)'' \leq 0$ , but this is rarely observed in nontrivial physical situations unless we pass to a (suitably renormalized) limit for  $n \rightarrow \infty$ . Nevertheless, there are (artificial from a physicist's point of view) examples where these conditions are met before passing to the limit. For instance, if  $E(x)$  is a positive homogeneous function on  $\mathbb{R}^n$  of degree  $p \geq 1$ , i.e.,  $E(\lambda x) = \lambda^p E(x)$ , then clearly  $\varphi(\rho) = \text{const } \rho^{n/p-1}$  and for  $\rho = n$  we obtain  $\beta_n = \frac{1}{p} - \frac{1}{n}$ , which can be replaced for our purposes by  $\frac{1}{p}$  for large  $n$ . Then, the measure  $\underline{\mu}_{\text{ca}} = C \rho^{n/p-1} e^{-\rho/p}$  concentrates near the value  $\rho = n$  in the sense that

$$\underline{\mu}_{\text{ca}}[n - \lambda\sqrt{n}, n + \lambda\sqrt{n}] \rightarrow 1$$

as  $\lambda \rightarrow \infty$ , where the convergence is uniform in  $n$  as an elementary computation shows (substitute  $\rho = t^2$  and appeal to the strict log-concavity of  $t^{2n/p} e^{-t^2/p}$ ).

Finally, let us estimate the distance between  $\mu_{\text{ca}}$  and  $\mu_{\text{mic}}$  on  $\mathbb{R}^n$  as follows. Denote by  $\delta$  the infimum of the radial derivatives of  $E(x)$  on the unit level  $S(1) = \{x \in \mathbb{R}^n : E(x) = 1\}$  and observe that the “annulus”

$$S_r(n) = \{x \in \mathbb{R}^n : \rho - r \leq E(x) \leq \rho + r\}$$

is contained in the  $s$ -neighborhood  $U_s(S(n))$  with  $s$  equal to about  $r/\delta n^{(p-1)/p}$ . It follows that most of the  $\mu_{\text{ca}}$ -measure is contained in  $U_s(S(n))$  with  $s = \lambda\delta^{-1}n^{\frac{1}{p}-\frac{1}{2}}$ , provided that  $\lambda$  is large (independently of  $n$ ). This agrees with our previous computation for  $E(x) = \sum_{i=1}^n x_i^2$  where  $p = 2$  and  $\delta = 2$ . Similarly, if  $E(x) = \sum_{p=1}^n x_i^p$ , then by a straightforward computation

$$\delta = \begin{cases} p & \text{for } p \leq 2 \\ pn^{\frac{1}{p}-\frac{1}{2}} & \text{for } p \geq 2 \end{cases}$$

and we get the (well-known) estimates

$$s = O(n^{\frac{1}{p}-\frac{1}{2}})$$

for  $p \leq 2$  and

$$s = O(1)$$

for  $p \geq 2$  (where the special role of  $p = 2$  is due to the quadratic nature of the Euclidean metric defining our  $s$ -neighborhood  $U_s(S(r))$ ).

Later on, we shall see, following G. Schechtman, how the above leads to the following bound on the  $\ell_p$ -ball

$$B_p(n^{1/p}) = \{x \in \mathbb{R}^n : \sum_{i=1}^n x_i^p \leq n\} :$$

$$\text{ObsDiam } B_p(n^{1/p}) = O(1),$$

i.e.,  $\text{ObsDiam}$  remains bounded for  $n \rightarrow \infty$ .

**3½.26. Concentration as ergodicity.** The ergodicity property of a measurable transformation can be expressed by saying that the orbit (saturation) of every subset of *positive* measure has *full* measure. Similarly, we may loosely say that an mm space  $X$  is “infinitely concentrated” if the  $\varepsilon$ -neighborhood of each subset  $X_0 \subset X$  with positive measure has full measure, where  $\varepsilon$  is an “infinitesimally small” number. Here, the relevant dynamics is the growth of subsets  $X_0 \mapsto X_\varepsilon = U_\varepsilon(X_0)$ , which in some cases comes from an ordinary flow. For example, if  $X$  is a Riemannian manifold, then  $U_\varepsilon(X_0)$  is obtained by first lifting (i.e., pulling back)  $X_0$  to the unit tangent bundle, say to  $\tilde{X}_0 \subset T_1(X)$  over  $X$ , then applying the geodesic flow

for the time  $t \in [0, \varepsilon]$ , and finally projecting the resulting  $[0, \varepsilon]$ -orbit of  $\tilde{X}_0$  back to  $X$ .

It is unclear if the ergodic analogy goes anywhere far on the technical level, but it certainly suggests many interesting questions. For example, one may ask what happens for more general, nonmetric “ $\varepsilon$ -saturations” of subsets  $X_0$  in a measure space  $X$  with a suitable structure, and many results here have been obtained by M. Talagrand (see [Tal]CMII). We also shall see later on how the ideas of *ergodic decomposition* and *dissipation* fare in the category of mm spaces.

**3½.27. Generalized Levy's inequalities.** Levy himself generalized the spherical isoperimetric inequality to convex hypersurfaces  $\Sigma^n \subset \mathbb{R}^{n+1}$  with principal curvatures  $\geq 1$ . Since then, his argument has been extended to all closed  $n$ -dimensional Riemannian manifolds  $V$  with  $\text{Ricci } V \geq n - 1 = \text{Ricci } S^n$  (see Appendix C<sub>+</sub> and [Croke]<sub>IIEE</sub>, [Gal]<sub>Iso</sub>, [Gal]<sub>IIA</sub>, [Gal]<sub>ES</sub>, [Ber-Gal]).

This extended Levy inequality implies that every such  $V$  (e.g., the above  $\Sigma^n$ ) satisfies  $(*)$  in (1) with the same constant  $\kappa_n$ . In particular,  $\text{ObsDiam}_{\mathbb{R}}(V; -\kappa) \leq \text{ObsDiam}_{\mathbb{R}}(S^n, -\kappa)$  for all  $\kappa > 0$ .

Another generalization concerns certain path metrics and measures supported in convex domains  $\Omega \subset S^n$  (we also allow  $\Omega = S^n$ ), where the geodesics of the metric coincide with the arcs of great circles, and where the measures  $\mu$  in question must satisfy some convexity condition somewhat similar to that implied by  $\text{Ricci} \geq \varepsilon > 0$ . Namely, assuming that  $\mu$  has a continuous density function, we define a *convex descendent*  $\nu$  of  $\mu$  on each geodesic arc  $I \subset \Omega$  as the weak (i.e.,  $\text{di}_1$ ) limit of the sequence  $\mu_i = (\mu|_{U_i})/\mu(U_i)$ , where  $U_i$  is a decreasing sequence of *convex* neighborhoods of  $I \subset \Omega$  with  $\bigcap_i U_i = I$ . (Notice that each arc  $I$  contained in a hemisphere  $I$  carries at least one convex descendent  $\nu$  of  $\mu$ , since we always can find  $U_i$  for which  $\mu_i$  converge and, in general, there may be many  $\nu$  on the same  $I$ ). Then the convexity of  $\mu$  refers to the convexity properties of the (density functions) of the measures  $\nu$  on the segments. In particular, one can measure the convexity (or rather concavity) of  $\mu$  by the “supremum of the *separation distances*” (see (1) 3½.30)

$$C_\lambda(\mu; \kappa) = \sup_{\nu} \text{Sep}(\nu; \kappa, \lambda\kappa),$$

where the sup is taken over all geodesic segments  $I \subset \Omega$  and all convex descendants  $\nu$  on  $I$ .

**Separation inequality ([Gro–Mil]GSII).** *The separation distance of a normalized measure  $\mu$  is bounded by*

$$\text{Sep}(\mu, \kappa, \lambda\kappa) \leq C_\lambda(\mu; \kappa) \quad (+)$$

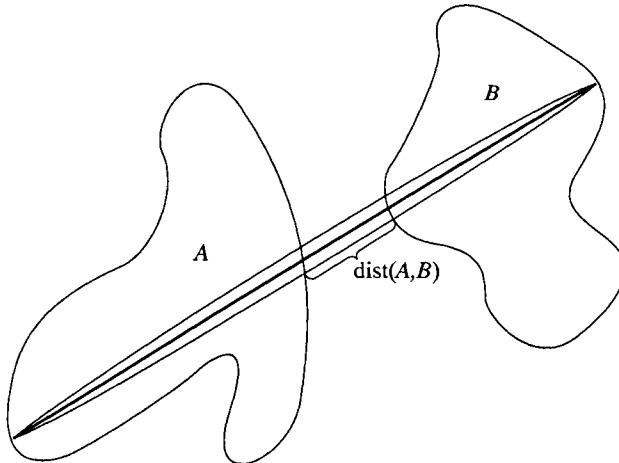
for all  $\kappa, \lambda > 0$ , where we assume that  $\mu$  is normalized by  $\mu(\Omega) = 1$ .

We shall indicate the proof below. Here, we observe that (+) rather easily yields the sharp spherical isoperimetric inequality when applied to the spherical measure  $\mu$  on  $S^n$ . Also, (+) gives the following bound on the observable diameter of the unit ball in the  $\ell_p$ -space  $(\mathbb{R}^n, \|\cdot\|_{\ell_p})$  for  $\|x\|_{\ell_p} = (\sum_i |x_i|^p)^{1/p}$ ,

$$\text{ObsDiam}_{\mathbb{R}}(B(1), -\kappa) \leq \text{const}_p(\kappa)/\sqrt{n}$$

for all  $1 < p < \infty$ , where the measure on  $B(1)$  in question is just the restriction of the Lebesgue measure from  $\nu \supset B(1)$  (see [Gro–Mil]GSII for a more precise statement applicable to all uniformly convex Banach spaces).

**Sketch of the proof of (+).** We want to bound the distance between two subsets  $A$  and  $B$  in  $\Omega \subset S^n$  with  $\mu(A) \geq \kappa$  and  $\mu(B) \geq \lambda\kappa$  by finding a segment  $I$  in  $\Omega$  with an “infinitely thin” convex neighborhood  $U$  (called a *needle* in [Kan–Lov–Sim]), such that  $\mu(U \cap A) \geq \kappa\mu(U)$  and  $\mu(U \cap B) \geq \lambda\kappa\mu(U)$ .

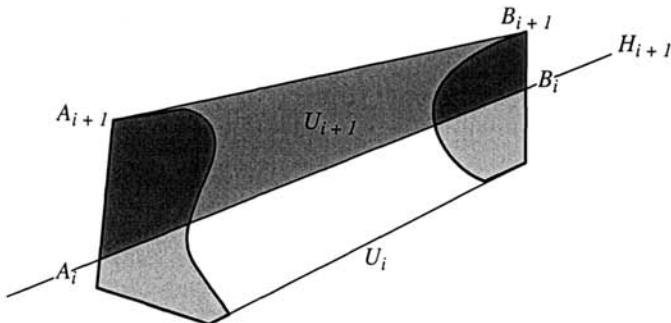


To put it another way, we need a descending sequence of convex domains  $U_1 \supset U_2 \supset \dots \supset U_i \supset \dots$  in  $S^n$  such that  $\mu(U_i \cap A) \geq \kappa\mu(U_i)$ ,  $\mu(U_i \cap B) \geq \lambda\kappa\mu(U_i)$ , and the intersection  $\bigcap_{i=1}^{\infty} U_i$  is 1-dimensional (i.e., a segment). Our construction of  $U_i$  is based on the (trivial special case of

the) Borsuk-Ulam theorem. This provides a hyperplane (i.e., an equatorial hypersurface)  $H_1$  in  $S^n$  dividing both  $A$  and  $B$  into equal halves, i.e., of measures  $\mu(A)/2$  and  $\mu(B)/2$ , respectively. We take the smaller of the two halves of  $S^n$  for  $U_1$ . Thus,  $U_1$  is a hemisphere with

$$\begin{aligned}\mu(U_1) &\leq \frac{1}{2} \\ \mu(U_1 \cap A) &= \mu(A)/2 \geq \kappa\mu(U_1) \\ \mu(U_2 \cap B) &= \mu(B)/2 \geq \lambda\kappa\mu(U_2).\end{aligned}$$

Then we apply the same procedure to  $A_1 = U_1 \cap A$  and  $B_1 = U_1 \cap B$  in place of  $A$  and  $B$ . Namely, we divide  $A_1$  and  $B_1$  into equal halves by a hyperplane  $H_2$  and take the smallest of the halves of  $U_1$  for  $U_2$ . Next, we pass to  $U_3$  by equi-dividing  $A_2 = U_2 \cap A_1$  and  $B_2 = U_2 \cap B_1$ , and so on.



It is clear that the limit  $I = \bigcap_{i=1}^{\infty} U_i$  must be one dimensional (otherwise we just keep dividing) and the proof follows.

**Remarks:** (a) The Borsuk-Ulam subdivision argument can also be applied to  $k$  subsets in  $S^n$  for  $k \geq 3$ , which leads to a bound on  $\text{Sep}(\mu, \kappa_1, \kappa_2, \dots, \kappa_k)$  in terms of  $(k-1)$ -dimensional convex descendants of  $\mu$ , but the merit of the resulting inequalities remains uncertain (compare (j)).

(b) There are other interesting classes of (nonconcave) measures  $\mu$  on  $S^n$  showing definite patterns of concentration, e.g., those given by polynomial densities of low degree, but little has been understood about them so far (compare [Bourg]).

(c) **Log-concavity.** Recall that a function  $\varphi$  on an affine space  $X$  is called *log-concave* (or *multiplicatively concave*) if

$$\varphi\left(\frac{x+y}{2}\right) \geq \sqrt{\varphi(x)\varphi(y)},$$

or equivalently, if  $\log(\varphi)$  is concave. If  $X = \mathbb{R}$ , then this is equivalent to  $(\log \varphi)'' \leq 0$ , and the  $\delta$ -sharp log-concavity refers to the inequality  $(\log \varphi)'' \leq -\delta < 0$ . The archtypical example is  $\varphi(x) = e^{-x^2/2}$ , which is 1-sharp log-concave, since  $(\log e^{-x^2/2})'' = -1$ . Similarly, one defines  $\delta$ -sharpness for log-concavity on  $\mathbb{R}^n$  by requiring this property for the restrictions of  $\varphi$  to all lines.

**Exercises:** (d) Show that every probability measure  $\mu$  on  $\mathbb{R}$  (or on a segment in  $\mathbb{R}$ ) with  $\delta$ -sharp log-concave density function is more concentrated than the Gaussian measure  $\mu_\delta = \sqrt{2\delta/\pi}e^{-\delta x^2/2}$  on  $\mathbb{R}$ , namely,

$$\text{Sep}(\mu; x, \lambda x) \leq \text{Sep}(\mu_\delta, x, \lambda x)$$

for all  $x, \lambda \geq 0$ .

(e) Show that the convex descendants of a log-concave measure  $\mu$  on  $\mathbb{R}^n$  are log-concave and  $\delta$ -sharpness is also inherited by the convex descendants of  $\mu$ .

(f) Prove an isoperimetric inequality for  $\delta$ -sharp log-concave functions generalizing the Gaussian isoperimetric inequality above.

(g) Show that the pushforwards of log-concave measures in convex domains in  $\mathbb{R}^n$  under linear projections  $\mathbb{R}^n \rightarrow \mathbb{R}^m$  are log-concave and that  $\delta$ -sharpness also persists under projections (compare the proof of the Brunn-Minkowski theorem in [Gro-Mil]\_GSII).

(h) Say that  $\varphi$  on  $\mathbb{R}^n$  is  $\delta$ -sharp in codimension  $k$  if it is log-concave, and for each  $x$ , there is an  $(n-k)$ -plane  $P \subset \mathbb{R}^n$  passing through  $x$  such that  $\varphi|_P$  is  $\delta$ -sharply log-concave on  $P$  at  $x$ , i.e.,  $\partial^2 \log \varphi \leq -\delta$  for all unit vectors  $\partial$  at  $x$  tangent to  $P$ . Show that a probability measure  $\mu$  on (a convex domain in)  $\mathbb{R}^m$ , with density  $\varphi^n$ , where  $\varphi$  is  $\delta$ -sharp in codimension  $k$ , concentrates near some  $k$ -plane  $F \subset \mathbb{R}^m$  in the following sense:

the  $\mu$ -measure of the complement of the  $\varepsilon\sqrt{m}$  neighborhood of  $F$  is  $\leq 2e^{-n\delta\varepsilon^2/2}$ .

(i) Prove that “ $\delta$ -sharp in codimension  $k$ ” is stable under linear projections of measures, as well as under passing to convex descendants of *all* dimensions  $\geq 1$  (as in (a)).

Combining (h) and (i) shows that linear projections of sufficiently sharp in codimension  $k$  measures from  $\mathbb{R}^n \rightarrow \mathbb{R}^m$  are concentrated near some  $k$ -dimensional linear subspaces. It is unclear how to prove a similar result

for nonlinear 1-Lipschitz maps  $\mathbb{R}^n \rightarrow \mathbb{R}^m$  where one wants the pushforward measures to concentrate near something of dimension  $\leq k$ . Nevertheless, we have the following alternative.

(j) Define the “ $k$ -dimensional distance”  $\Delta_k(A_0, \dots, A_k)$  for  $A_i \subset \mathbb{R}^n$  as the infimum of the  $k$ -volumes of the  $k$ -simplices in  $\mathbb{R}^n$  with vertices  $a_i \in A_i$ . Then give a lower bound on  $\Delta_k(A_0, \dots, A_k)$  in terms of  $\mu(A_i)$ ,  $i = 0, \dots, k$ , for a probability measure  $\mu = \varphi dx$ , where the density  $\varphi$  is  $\delta$ -sharp in codimension  $k - 1$  in some convex domain in  $\mathbb{R}^n$ . (*Hint:* See (a).)

(k) **Convexity and log-convexity.** The Brunn theorem states that the pushforward of the Lebesgue measure  $dx$  on a convex subset  $X$  in  $\mathbb{R}^n$  becomes  $\sqrt[k]{\cdot}$ -concave under the projection  $\mathbb{R}^n \rightarrow \mathbb{R}^{n-k}$ , where the  $\sqrt[k]{\cdot}$ -concavity of a measure  $\varphi dx$  means concavity of  $(\varphi)^{1/k}$  at the points where  $\varphi > 0$ . More generally,  $\sqrt[\alpha]{\cdot}$  concave measures in (convex domains in)  $\mathbb{R}^n$  go to  $\sqrt[\beta]{\cdot}$ -concave ones in (convex domains in)  $\mathbb{R}^m$  for  $\alpha - \beta = n - m$ , as a simple induction on  $n - m$  shows (see [Gro-Mil]<sub>Brunn</sub>). Furthermore, a suitably defined strict (or sharp)  $\sqrt[\alpha]{\cdot}$ -concavity should descend to the corresponding strict (or sharp)  $\sqrt[\beta]{\cdot}$ -concavity of the projection, where we want to model such a descent on what happens to the projection of  $dx$  on the round ball  $B \subset \mathbb{R}^n$  as it projects to  $\mathbb{R}^{n-k}$  and then to  $\mathbb{R}^{n-\ell}$ ,  $\ell > k$ . We suggest that the reader investigate this more carefully (perhaps by looking through the literature).

Here, we indicate how to derive possible corollaries concerning the concentration of the projections by approximating the Lebesgue measure  $dx$  on a convex body  $X \subset \mathbb{R}^n$  by a log-concave measure. To do this, we assume that  $X$  contains the origin and then consider the associated “norm”  $\|x\|_0$  on  $\mathbb{R}^n$ , i.e., the homogeneous positive function equal to one on the boundary of  $X$ . Now we take the measure  $e^{-\|x\|_0^2} dx$  and observe that the sharpness of the log concavity of this measure reflects the strictness of the convexity of  $X$ . On the other hand, most of this measure is concentrated in a narrow band of width about  $1/\sqrt{n}$  around  $\partial X$ , and so the concentration properties of functions on  $X$  (or  $\partial X$ ) with respect to  $dx$ , as well as those of projections  $X \rightarrow \mathbb{R}^m$ , can be derived from the corresponding properties of  $e^{-\|x\|_0^2}$  (compare 3.24).

(k') Suppose that  $X$  is strictly convex in codimension  $k$ , which signifies here that at each boundary point  $x \in X$ ,  $k - n - 1$  (out of  $n - 1$ ) principal curvatures of  $X$  are  $\geq 1$ , where  $\partial X$  is assumed  $C^2$ -smooth for the sake of simplicity. Then every orthogonal projection  $X \rightarrow \mathbb{R}^m$  concentrates near some  $k$  plane  $F$ , i.e., of the measure  $dx$  on  $X$  pushed forward to  $\mathbb{R}^m$  in the

What would be more interesting is to prove similar concentration of every 1-Lipschitz map  $X \rightarrow \mathbb{R}^m$  with  $F$  replaced by a more general (nonflat)  $k$ -dimensional subset.

( $k''$ ) Use  $e^{-\|x\|_0^2} dx$  to prove the isoperimetric inequality from [Gro–Mil]<sub>GSII</sub> for uniformly convex Banach spaces.

**3½.28. Subvarieties in  $S^n$ ,  $\mathbb{RP}^n$ , and  $\mathbb{CP}^n$ .** Consider a submanifold  $X \subset S^n$  of codimension  $k$  which satisfies the following two conditions:

- (i)  $X$  meets each  $k$ -dimensional equatorial sphere in  $S^n$  in at most  $d$  points.
- (ii)  $\text{vol}_{n-k} X \geq c \text{vol } S^{n-k}$ .

(Notice that necessarily  $c \leq d/2$ , since the average number of intersection points of  $X$  with equatorial  $k$ -spheres equals  $2 \text{vol}_{n-k}(X) / \text{vol } S^{n-k}$  by the Crofton formula. Also observe that (i) is satisfied with  $d = d(\delta)$  for semialgebraic subsets in  $S^n$  of degree  $\delta$ .) Take a subset  $X_0 \subset X$  of relative measure  $\kappa$  (i.e.,  $\text{vol}_{n-k}(X_0) = \kappa \text{vol}_{n-k}(X)$ ) and observe that the  $\varepsilon$  neighborhood of  $X_0$  in  $S^n$  satisfies

$$\mu(U_\varepsilon(X_0)) \geq \kappa_\varepsilon = 2cd^{-1}b(k, \varepsilon)\kappa, \quad (*)$$

where  $\mu = \mu_n$  denotes the normalized  $O(n)$ -invariant measure (volume) in  $S^n$  and  $b(k, \varepsilon)$  is the  $\mu_k$ -measure of the  $\varepsilon$ -ball in  $S^k$ , where  $\mu_k$  is also normalized. This follows from Crofton's formula, since every equatorial  $S^k$  meeting  $X_0$  contains an  $\varepsilon$ -ball inside  $U_\varepsilon(Y)$  (compare [Milm]). Then we can estimate the distance between two such subsets, say  $X_0$  and  $X_1$ , in  $X$  by the distance between  $U_\varepsilon(X_0)$  and  $U_\varepsilon(X_1)$  plus  $2\varepsilon$ , which allows a bound on  $\text{ObsDiam } X$  by  $\text{ObsDiam } S^n$  related to the *separation distance* (see 3½.3D). Namely,

$$\begin{aligned} \text{ObsDiam}(X; -2\kappa) &\leq \text{Sep}(X; \kappa, \kappa) \\ &\leq \text{Sep}(S^n; \kappa_\varepsilon, \kappa_\varepsilon) + 2\varepsilon \\ &\leq \text{ObsDiam}(S^n, -\kappa_\varepsilon) + 2\varepsilon \\ &\leq \frac{2\sqrt{2}}{\sqrt{n}} \sqrt{-\log(\kappa_\varepsilon/2)} + 2\varepsilon \\ &\leq \frac{2\sqrt{2}}{\sqrt{n}} \sqrt{-\log(2cd^{-1}b(k, \varepsilon)\kappa)} + 2\varepsilon. \end{aligned}$$

To make use of this, we have to bound  $b(k, \varepsilon)$  from below and then judiciously choose  $\varepsilon$ . We roughly estimate  $b(k, \varepsilon) \geq (\varepsilon/3)^k$  (by looking at the

measure  $(\cos t)^k dt$  on  $[-\pi/2, \pi/2]$ ) and take  $\varepsilon = \sqrt{k/n}$ . Then we get

$$\text{ObsDiam}(X, -\kappa) \leq \sqrt{\frac{k}{n}} \left( 4 + \sqrt{-\log \left( \frac{k}{n} cd^{-1} \kappa \right)} \right), \quad (+)$$

which is only slightly more than  $\sqrt{k/n}$  for each given  $\kappa > 0$  and  $cd^{-1} \geq \text{const.}$  Actually, this “more” seems excessive and the best possible (but maybe impossible?) inequality should read

$$\text{ObsDiam}(X, -\kappa) \leq \sqrt{\frac{k}{n}} (C_1 + C_2 \sqrt{-\log(cd^{-1} \kappa)}).$$

**Exercise:** Consider the union  $X = S_1^{n-k} \cup S_2^{n-k}$  of two mutually orthogonal equators  $S_1^{n-k}$  and  $S_2^{n-k}$  in  $S^n$  and show that the observable diameter of this  $X$  is about  $\sqrt{k/n}$  (compare (e) below).

*The case of  $\mathbb{CP}^n$ .* The Hopf fibration  $S^{2n+1} \rightarrow \mathbb{CP}^n$  tells us that  $\mathbb{CP}^n \prec S^{2n+1}$  (in the sense of 3.1.16), and so

$$\text{ObsDiam } \mathbb{CP}^n \leq \text{ObsDiam } S^{2n+1} \leq 1/\sqrt{n}.$$

Furthermore, the above argument carries over to subsets  $X \subset \mathbb{CP}^n$  and applies in particular to *complex algebraic*  $X$  where (properly redefined)  $d/c$  equals 1. It follows that

$$\text{ObsDiam}(X, -\kappa) \leq 10 \sqrt{\frac{k}{n}} \sqrt{-\log \frac{k}{n} \kappa} \quad (+)_C$$

for all complex algebraic subvarieties of complex codimension  $k$  with the normalized  $(2n - 2k)$ -dimensional measure (volume) and the distance induced from the standard ( $U(n+1)$ -invariant) Fubini–Study metric on  $\mathbb{CP}^n$ . (Again, we would prefer a slightly better bound with  $\log \kappa$  instead of  $\log(\frac{k}{n} \kappa)$ .)

**Remarks:** For small  $k/n$ , these concentrated spaces do not display an essentially new geometry compared to the spheres and/or projective spaces, since these  $X$  are  $\sqsubseteq_1$ -close to spheres and to the complex projective spaces. In fact, the proof above shows that the normalized Riemannian measure on such  $X \subset S^n$  (or  $\subset \mathbb{CP}^n$ ) is only slightly farther than  $\sqrt{k/n}$  from the ambient spherical (Fubini–Study in  $\mathbb{CP}^n$ ) measure for our  $d_{1,1}$ -metric on measures. (One may observe here the obvious continuity of the function  $X \mapsto \text{ObsDiam}(X, -\kappa)$  with respect to the metric  $\sqsubseteq_1$ .) Furthermore, our argument suggests the following “ $\varepsilon$ -order” on measures on a metric space  $S$

$$\mu \geq_\varepsilon \nu \Leftrightarrow \mu(U_\varepsilon(Y)) \geq b(\varepsilon) \nu(Y)$$

for all  $Y \subset S$  and a given function  $b(\varepsilon)$  specifying this “order.”

We suggest that the reader pursue this train of thought by studying the formal properties of the  $\varepsilon$ -order and by bringing forth further examples.

**Question:** When can one strengthen the above inequalities, e.g., (+), by allowing the induced *path* metric in subsets  $X$  of  $S^n$  (or  $\mathbb{C}P^n$ ) rather than the induced distance function?

**Examples:** Let  $X$  be the union of two  $(n - 1)$ -spheres in  $S^n$ . Since these  $S_1^{n-1}$  and  $S_2^{n-1}$  meet along  $S^{n-2}$  whose small neighborhoods in  $S_1^{n-1}$  and  $S_2^{n-1}$  have nearly the full volume, this  $X = S_1^{n-1} \cup S_2^{n-1}$  has essentially the same concentration as a single  $S^{n-1}$ . Similarly, the union  $X$  of  $d$  equatorial spheres of codimension  $k$  in  $S^n$  is highly concentrated for large  $n$  if  $k$  and  $d$  are small compared to  $n$ . What is somewhat more amusing, the concentration remains high even if  $d \rightarrow \infty$  as fast as we want (with  $k$  bounded). To see this from another angle, let  $X$  be obtained by attaching  $d$  copies of the hemisphere  $S_+^n$  to  $S^n$  along equators  $S_i^{n-1}$  in  $S^n$  identified with  $\partial S_+^n$ . Then  $\text{ObsDiam } X \leq 1/\sqrt{n}$  independently of  $d$ , where we can use the obvious path metric and the normalized measure in  $X$ . In fact, every subset  $X_0 \subset X$  of measure  $\kappa$  contains at least  $\kappa$ ’s part of measure of some of  $S_{+i}^n$ . Then the  $\varepsilon$ -neighborhood  $U_\varepsilon(X_0)$  bites away about  $\kappa$  relative measure of the boundary (equator)  $S_i^{n-1}$ , and then  $U_{2\varepsilon}(X_0) = U_\varepsilon(U_\varepsilon(X_0))$   $\kappa$ -penetrates into the central sphere  $S^n$ . It follows that  $U_{3\varepsilon}(X_0)$  and  $U_{3\varepsilon}(X_1)$  necessarily meet in  $S^n$  (and also in each  $S_{+i}^n$ ) if  $\kappa$  is not terribly small.

**Corollary to the proof:** *Finite spherical buildings  $X$  of dimension  $n$  are concentrated at least as strongly as  $S^n$ , thus having*

$$\text{ObsDiam}(X, -\kappa) \leq \frac{5}{\sqrt{n}} \sqrt{-\log \kappa}.$$

Here we include the 5 to play it safe.

This may look impressive (especially if you have never heard of Tits’ buildings before), but, alas, it reveals precious little new measure geometry compared to the basic Levy theorem.

**Exercises:** (a) Evaluate more carefully the observable diameter of the union of  $d$  spheres in  $S^n$ ,

$$X = S_1^{n-k_1} \cup S_2^{n-k_2} \cup \dots \cup S_d^{n-k_d} \subset S^n.$$

(b) Do the same for the union of planes  $\mathbb{C}P_i^{n-k_i}$  in  $\mathbb{C}P^n$  and for quaternionic planes in  $\mathbb{H}P^n$ .

(c) Estimate the observable diameter of the product of spheres, say  $S^m \times S^m \times \cdots S^m$  for large  $m$  and small numbers of factors by embedding this product into  $S^{km+k-1}$ . Do the same for the Stiefel manifold of orthogonal  $k$  frames in  $\mathbb{R}^n$ .

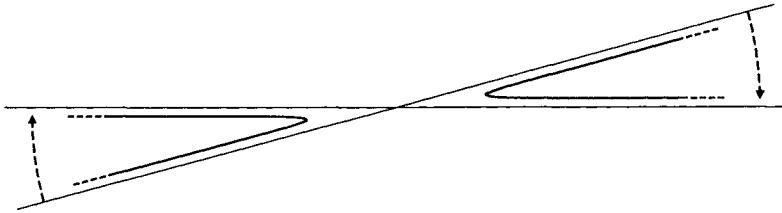
(d) Estimate the observable diameter of the Grassmannian space of  $k$  planes in  $\mathbb{R}^n$  via the natural fibration  $\text{St}_k \rightarrow \text{Gr}_k$  giving the Lipschitz majorization  $\text{Gr}_k \prec \text{St}_k$ .

**Remarks:** The estimates suggested in (b) and (d) appear in [Milm]<sub>APP</sub>, [Milm]<sub>HPL</sub>, and [Mil-Sch]. These extend to more general homogeneous submanifolds  $X \subset S^n$  of *low codimension* and also to some non homogeneous submanifolds  $X$  in  $S^n$  with bounded relative curvatures (i.e., the second fundamental form) such as *isoparametric hypersurfaces* dividing  $S^n$  into equal halves. But for many compact symmetric spaces  $X$ , better estimates follow from the generalized Levy's isoperimetric inequality (depending on  $\inf \text{Ricci } X$ , see [Gro-Mil]<sub>GSII</sub>). Probably asymptotically sharp bounds on  $\text{ObsDiam } X$  for symmetric spaces of rank  $r \rightarrow \infty$  *cannot* be derived from similar inequalities for  $S^n$ , since one can expect a lower bound on  $\square_1(X_1, X_2)$  for symmetric spaces  $X_1$  and  $X_2$  in terms of  $\text{rank } X_1 / \text{rank } X_2$ . One also does not think of a good(?) majorization  $X_1 \prec X_2$  for  $\text{rank } X_1 \gg \text{rank } X_2$ . Nevertheless, one hopes to eventually find asymptotically sharp values of  $\text{ObsDiam } X^n$ ,  $n = 1, 2, \dots$ , for the classical sequence of compact symmetric spaces as well as for the isoperimetric profiles of these spaces. One may even aspire to do the same for all compact homogeneous spaces, but the only known systematic approach to these problems comes from spectral geometry (see 3 $\frac{1}{2}$ .G).

**3 $\frac{1}{2}$ .29. Concentration for  $(X, \text{DIST}) \subset \mathbb{C}\text{P}^k$ .** Now we turn to (the concentration problem for) complex algebraic varieties  $X$  in  $\mathbb{C}\text{P}^n$  of low codimension  $k$  and degree  $d$ . We take the induced *path metric*  $\text{DIST}$  on  $X$  and the normalized Riemannian volume. This  $\text{DIST}$  may be significantly greater than the induced distance function  $\text{dist} = \text{dist}_{\mathbb{C}\text{P}^n}|_X$ . In fact, the ratio  $\text{DIST} / \text{dist}$  blows up for some degenerating families of algebraic varieties, e.g., for the quadrics  $X_\varepsilon = y(y + \varepsilon x) = 1$  as  $\varepsilon \rightarrow 0$ , in the plane  $\mathbb{C}^2 \subset \mathbb{C}\text{P}^2$ .

However, we shall see below that this blowup is (essentially) limited to a subset of relatively small measure in  $X$ . Consequently, we shall prove in (G'') that  $\text{ObsDiam}(X; -\kappa)\text{DIST}$  decays at least as fast as  $(\log(n)/n)^{1/2d}$  for  $n \rightarrow \infty$  if  $d, k$ , and  $\kappa$  are kept fixed or grow much slower than  $n$ .

Our analysis of the relevant geometry of  $X$  depends on locating a subvariety  $\Sigma \subset X$  of codimension  $d - 1$  such that



- (i) Almost all measure of  $X$  lies  $\varepsilon$ -close to  $\Sigma$  with respect to DIST, where  $\varepsilon \rightarrow 0$  as  $n \rightarrow \infty$ ;
- (ii) The metric DIST near  $\Sigma$  can be bounded in terms of dist in a manner independent of  $m = \dim X$  (but dependent on  $d$  and  $k$ ).

This  $\Sigma$  appears as a certain singularity of a suitable projection of  $X$  from  $\mathbb{C}P^n$  to a subspace  $\mathbb{C}P^m$  in  $\mathbb{C}P^n$  as follows.

**(A) Projections  $X \rightarrow \mathbb{C}P^m$  and the loci  $\Sigma \subset X$  of maximal multiplicity.** Consider two mutually *opposite* subspaces in  $\mathbb{C}P^n$  of dimensions  $m$  and  $k-1 = n-m-1$ , where “opposite” corresponds to orthogonality between the corresponding linear subspaces of dimensions  $m+1$  and  $k$  in  $\mathbb{C}^{n+1}$ . Then we *project*  $\mathbb{C}P^n$  to our  $\mathbb{C}P^m$  from the opposite  $\mathbb{C}P^k$ , called the *center* of the projection. This means that every  $x \in \mathbb{C}P^n$  goes to the intersection of  $\mathbb{C}P^m$  with the  $k$ -plane  $P$  in  $\mathbb{C}P^n$  passing through  $\mathbb{C}P^{k-1}$  and  $x$ . This projection is well-defined and regular on the complement  $\mathbb{C}P^n \setminus \mathbb{C}P^{k-1}$ ; we shall apply it to an  $m$  dimensional subvariety  $X \subset \mathbb{C}P^n$  which misses  $\mathbb{C}P^{k-1}$ .

**Bézout theorem.** *The projection  $p: X \rightarrow \mathbb{C}P^m$  is finite-to-one. In fact, there is an integer  $d$  such that  $\text{card}(p^{-1}(y)) = d$  for  $y \in \mathbb{C}P^m \setminus \underline{\Sigma}^1$ , where  $\underline{\Sigma}^1$  is a hypersurface in  $\mathbb{C}P^m$  (which is empty for  $d=1$ ). This  $d$  is independent of the choice of the  $(k-1)$ -plane  $\mathbb{C}P^{k-1} \subset \mathbb{C}P^n$  from where we project and is called the degree  $\deg X$ .*

**Remark:** Judging by the name, this result was probably first proved by anybody but Bézout. A novice reader may enjoy finding a proof on his/her own.

**Local and global degrees.** Let  $p: X \rightarrow Y$  be a holomorphic map between complex analytic varieties, where  $Y$  is assumed to be nonsingular. The (*local*) *degree* of  $p$  at a point  $x \in X$  is defined as the integer  $d_x$  with the following property. There exist neighborhoods  $U_x \subset X$  of  $x$  and  $\underline{U}_* \subset Y$  of  $p(x) \in Y$  and a complex hypersurface  $\underline{\Sigma}_x^1 \subset Y$  such that

$$\text{card}(p^{-1}(y) \cap U_x) = d_x$$

for all  $y \in \underline{U}_* \setminus \underline{\Sigma}_x^1$ .

The existence of these  $U_x, \underline{U}_x$ , and  $\underline{\Sigma}_x^1$  follows by an easy (and standard) variation of the Bezout tune (where we observe that one can choose  $\underline{\Sigma}_x^1$  independent of  $x$  in our case where  $X, Y$ , and  $p$  are algebraic). Furthermore, the global degree  $d$  of our  $p: X \rightarrow Y = \mathbb{C}\mathrm{P}^m$  satisfies

$$d = \sum_{x \in p^{-1}(y)} d_x \quad (*)$$

for all  $y \in \mathbb{C}\mathrm{P}^m$ . In particular,  $d_x \leq d$  for all  $x \in X$ .

Actually, this is true (“well-known and easy to prove,” as the poor reader might have learned by now) for arbitrary proper holomorphic maps (and even for continuous maps with suitable definitions of  $d$  and  $d_x$ ). And  $(*)$  obviously implies the following

**(A') One-to-One Corollary:** Let  $\Sigma \subset X$  consist of those  $x \in X$  where  $d_x = d$  and set  $\underline{\Sigma} = p(\Sigma) \subset \mathbb{C}\mathrm{P}^m$ . Then  $p$  is one-to-one over  $\underline{\Sigma}$ , i.e.,  $\mathrm{card}(p^{-1}(y)) = 1$  for all  $y \in \underline{\Sigma}$ .

Now we ask ourselves: how large are  $\Sigma$  and  $\underline{\Sigma}$ ? Here is our

*Answer: These  $\Sigma \subset X$  and  $\underline{\Sigma} \subset \mathbb{C}\mathrm{P}^m$  are algebraic subvarieties of codimension  $\leq k(d - 1)$ .*

**Proof.** The fiber  $p^{-1}(y)$ ,  $y \in \mathbb{C}\mathrm{P}^m$ , equals the intersection of  $X$  with the  $k$ -plane  $P_y$  in  $\mathbb{C}\mathrm{P}^n$  passing through  $y$  and containing the center  $\mathbb{C}\mathrm{P}^{k-1}$ . This intersection  $X \cap P_y$  consists of  $d$  points  $x_i = x_i(y)$  if we count with multiplicities, and  $y$  belongs to  $\underline{\Sigma}$  if and only if all  $d$  points collide, i.e.,  $\mathrm{card}(X \cap P_y) = 1$ . This collision can be expressed by  $d - 1$  equations

$$x_1(y) = x_2(y) = \cdots = x_d(y),$$

where each of these represents a system of  $k$  numerical equations as  $x_i$  sum over  $P_y = \mathbb{C}\mathrm{P}^k$ . So, we have  $k(d - 1)$  equations altogether, which suggests the equalities  $\mathrm{codim} \Sigma = \mathrm{codim} \underline{\Sigma} = k(d - 1)$ .

Now, to give an actual proof, we observe that our projection  $\mathbb{C}\mathrm{P}^n \setminus \mathbb{C}\mathrm{P}^{k-1} \rightarrow \mathbb{C}\mathrm{P}^m$  makes a vector bundle over  $\mathbb{C}\mathrm{P}^m$  with fiber  $P_y \setminus \mathbb{C}\mathrm{P}^{k-1}$ ,  $y \in \mathbb{C}\mathrm{P}^m$ . This vector bundle (obviously) splits into a sum of  $k$  line bundles, each being isomorphic to the normal bundle of  $\mathbb{C}\mathrm{P}^m \subset \mathbb{C}\mathrm{P}^{m+1}$ . First let  $k = 1$ , where we are left with a single line bundle  $L \rightarrow \mathbb{C}\mathrm{P}^m$ . The equations  $x_1 = x_2 = \cdots = x_d$  for the symmetric configuration of points  $\{x_i = x_i(y)\}$  in each fiber  $L_y \subset L$  can be rewritten in terms of the symmetric functions as follows

$$\sum_{i=1}^d x_i^r = \frac{1}{d^{r-1}} \left( \sum_{i=1}^d x_i \right)^r,$$

$r = 2, \dots, d$ . Here the first equation with  $r = 2$  refers to the tensor square  $L^2 = L \otimes L$ , the second to  $L^3 = L \otimes L \otimes L$ , etc., where we use the canonical maps  $L \rightarrow L^r$  sending each  $x$  to  $x^r \in L^r$ . Thus, the solutions of the  $r$ -th equation correspond to the zeros  $Z_r \subset \mathbb{C}\mathbf{P}^m$  of the section  $s_r = \sum_{i=1}^r x_i^r - \left(\sum_{i=1}^d x_i\right)^r / d^{r-1}$  of  $L^r$ . Every such  $Z_r$  is a hypersurface in  $\mathbb{C}\mathbf{P}^m$  of degree  $r$  (unless it coincides with  $\mathbb{C}\mathbf{P}^m$ ), and so their intersection

$$\underline{\Sigma} = Z_2 \cap Z_3 \cap \cdots \cap Z_d \subset \mathbb{C}\mathbf{P}^m$$

has codimension  $\leq d-1$  (and degree  $d!$ ). Thus, the case  $k = 1$  is concluded.

Finally, let  $k \geq 2$  and look at  $x_1, \dots, x_d$  in the sum of  $k$  line bundles, say in  $L_1 \oplus \cdots \oplus L_j \oplus \cdots \oplus L_k$ . Then, clearly,  $\underline{\Sigma}$  contains the intersection

$$\bigcap_{\substack{r=2,\dots,d \\ j=1,\dots,k}} Z_{r,j},$$

and so both  $\underline{\Sigma}$  and  $\Sigma$  have codimension  $\leq k(d-1)$  (where  $\deg \underline{\Sigma} \leq (d!)^k$  and  $\deg \Sigma \leq d(d!)^k$ ).

**Remarks:** (a) One can think of  $\Sigma \subset X$  as a cycle representing the dual to a certain characteristic class  $\delta_d(X) \in H^*(X)$ , at least when  $X$  is smooth. Actually, this  $\delta_d$  must lie in  $H^{2m-2d+2}(X)$  and whenever  $\delta_d \neq 0$ , every holomorphic map  $p: X \rightarrow \mathbb{C}\mathbf{P}^m$  of degree  $d$  will have  $\text{codim } \Sigma \geq d-1$  (where  $\Sigma$  is defined as the set of points  $x \in X$  where  $d_x = d$ ). This suggests that the codimension of our  $\Sigma$  and  $\underline{\Sigma}$  for  $X = \mathbb{C}\mathbf{P}^n$  must be  $\leq d-1$  for all codimensions  $k = 1, 2, \dots$ . This is not true, however, since our bound  $\text{codim } \leq k(d-1)$  is sharp for  $X$  equal to the union of several  $m$  planes in  $\mathbb{C}\mathbf{P}^n$  meeting transversally. But it is true for all smooth  $X$  and for complete intersections. In fact, every holomorphic map  $p$  of a normal (e.g., nonsingular) variety  $X$  into  $\mathbb{C}\mathbf{P}^n$  has  $d$  points coming together along a subvariety of codimension  $\leq d$  for  $d = \deg_{\text{top}} p$  (see [Ga-La]; this was pointed out to me by Fedia Zak).

(b) One can easily arrange a hypersurface  $X \in \mathbb{C}\mathbf{P}^{m+1}$  where  $\text{codim } \Sigma < d-1$ ; just take  $d \geq 3$  hyperplanes meeting along an  $(m-2)$ -plane. One can also produce examples with nonsingular  $X$  and special  $p$ , such as a plane cubic curve  $X$  projected from a center lying on a line tangent to  $X$  at an inflection point in  $X$ . We suggest working out further examples to the reader, who may also try to figure out if  $\text{codim } \Sigma = d-1$  for every nonsingular hypersurface  $X$  and a generic projection  $p$  (which seems easy to me). For example, if  $X \subset \mathbb{C}\mathbf{P}^{m+1}$  is a nonsingular quadric, then  $\underline{\Sigma} \subset \mathbb{C}^m$

is also a nonsingular quadric hypersurface for every center  $c_0 = \mathbb{C}\mathbf{P}^0 \subset \mathbb{C}\mathbf{P}^{m+1} \setminus X$ . And  $p: X \rightarrow \mathbb{C}\mathbf{P}^m$  is a ramified double cover which branches exactly along  $\underline{\Sigma}$ , while  $\Sigma = p^{-1}(\underline{\Sigma})$  equals the singular set of  $p$  where  $\text{Jacobian}(p) = 0$ .

(c) Persistence (or disappearance) of our  $\Sigma$  with  $\text{codim } \Sigma = d - 1$  implies nonvanishing (or vanishing) of the corresponding characteristic class  $\delta(X) \in H^{2m-2d+2}(X)$  under suitable algebraic geometric assumptions. The key point is the *non-vanishing* of the  $2r$ -dimensional homology classes in  $H_{2r}(X; \mathbb{R})$  represented by  $r$ -dimensional algebraic subvarieties  $Y$  in  $X$  (with  $r = d - 1$  in the case of  $Y = \Sigma$ ). This nonvanishing is due to the *positivity* of the intersection of each  $Y$  with a generic  $(N - r)$ -plane  $P$  in some ambient projective space  $\mathbb{C}\mathbf{P}^N \supset X \supset Y$ , which makes  $[Y]$  nonzero in  $H_{2r}(\mathbb{C}\mathbf{P}^N)$  and thus in  $H_{2r}(X)$ . (Notice that complex (sub)varieties come along with natural orientations, and so intersection indices are well-defined. Also, the intersection with  $P$  gives us the degree of  $Y$  by the Bezout theorem.)

Here is another (well-known) instance of this phenomenon, where the topology of a map is strongly influenced by its algebraic geometric origin.

*Let  $p$  be a surjective holomorphic map between equidimensional complex algebraic manifolds, say  $p: X \rightarrow A$ , (where, actually, one can admit an arbitrary complex manifold for  $A$ ). If  $p^*: H^2(A) \rightarrow H^2(X)$  sends the first Chern class  $c_1(A)$  to  $c_1(X)$ , then  $p$  is a covering map. In particular, if  $A$  is simply connected, then  $p$  is an isomorphism.*

In fact, the Jacobian (determinant) of a noncovering map  $p$  must vanish on a subvariety  $\Sigma_0 \subset X$  with  $\text{codim } \Sigma_0 \leq 1$ , and the cohomological dual to  $[\Sigma_0]$  corresponds to the difference  $p^*(c_1(Y)) - c_1(X)$ .

One can say slightly more if the receiving space  $A$  is complex parallelizable, i.e., admits a full frame of holomorphic vector fields, or, equivalently, of holomorphic 1-forms. In this case, the condition  $c_1(X) = 0 (= c_1(A))$  implies that a holomorphic map  $p: X \rightarrow A$ , which is not assumed to be surjective, necessarily has *constant rank*, thus decomposing into a holomorphic fibration  $X \rightarrow \underline{X}$  followed by an immersion  $\underline{X} \hookrightarrow A$ , where this immersion is *parallel* with respect to the parallelization of  $A$ . This means that the isomorphism between the tangent spaces of  $A$  given by the frames sends  $T_a(\underline{X}) \rightarrow T_b(\underline{X})$  for all  $a, b \in X$ . We leave the proof of this to the reader, and we also indicate the following classical corollary.

*Let  $X$  be an algebraic manifold with  $c_1(X) = 0$  and  $\text{rank } H^1(X) \geq 2m$  for  $m = \dim_{\mathbb{C}} X$ . Then  $X$  is isomorphic to a complex torus, i.e.,  $\mathbb{C}^{2m}/\text{lattice}$ .*

**Proof.** One knows that  $X$  admits a holomorphic map to some torus  $p: X \rightarrow A = \mathbb{C}^{2k}/\text{lattice}$  for  $2k = \text{rank } H^1(X)$  (where  $A$  is called the *Albanese variety* and  $p$  is the *Abel–Jacobi–Albanese map*), such that  $p^* H^1(A) = \mathbb{Z}^{2k} \rightarrow H^1(X)$  is an isomorphism. This  $p$  factors as  $X \rightarrow \underline{X} \hookrightarrow A$  with an immersed *subtorus*  $\underline{X} \hookrightarrow A$  which must necessarily have real dimension  $2k$  to make  $p_*$  an isomorphism. Since  $2k \geq 2m$ , we are left only with the possibility of  $2k = 2m$  and  $p: X \rightarrow A$  being a finite covering map.

(d) The above can be sharpened with the notion of *positivity* on cohomology  $H^2(X)$ . For example, the conclusion that  $X$  is a torus holds whenever  $\text{rank } H^1(X) \geq 2 \dim X$  and  $-c_1(X)$  is *non positive*, i.e., there is *no* complex algebraic hypersurface  $Y \subset X$  with the class  $[Y] \in H_{2m-2}(X)$  being dual to a *negative* multiple of  $c_1(X)$ . On the other hand, there are deeper relations between Chern classes, such as the Bogomolov–Miyoaka–Yau inequality  $c_2 \geq 3c_1^2$  for surfaces of general type, or Yau’s theorem:  $c_1 = c_2 = 0 \Rightarrow X = \text{torus}$ , which go beyond mere positivity.

**(B) Controlling the center**  $\mathbb{CP}^k \subset \mathbb{CP}^n \setminus X$ . We now plunge into the muddy waters of mixed algebraic and metric geometry, and we invite the courageous reader to swim along through a dozen pages until the finish in  $(G''')$ .

Our first objective is to position  $\mathbb{CP}^k$  far from  $X$  in order to protect the projection  $p: X \rightarrow \mathbb{CP}^m$  from exploding. Here is the relevant

**(B') Lemma:** *For every  $\ell < \text{codim } X$ , there exists an  $\ell$ -plane  $\mathbb{CP}^\ell \subset \mathbb{CP}^n$  lying  $\varepsilon$ -far from  $X$  (i.e., in the complement of the  $\varepsilon$ -neighborhood of  $X$ ) for  $\varepsilon \geq \varepsilon_{\ell,d} \geq (10d)^{-(\ell+1)}$  and  $d = \deg X$ .*

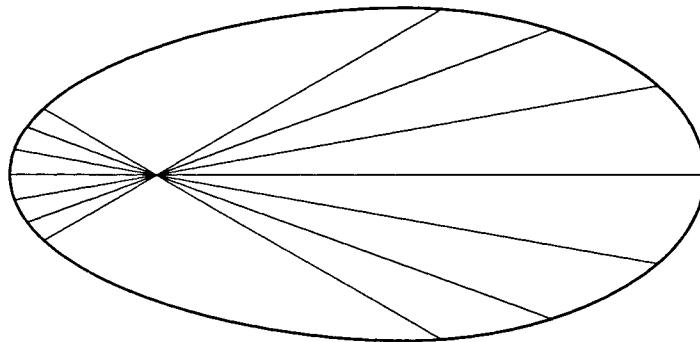
**Proof.** Everything is based on the

**Bernstein inequality.** *Let  $Q(x)$  be a complex polynomial of degree  $d$  on  $\mathbb{C}^n$ . Then the supremum of the gradient of  $Q$  over an  $R$  ball  $B \subset \mathbb{C}^n$  satisfies*

$$\sup_{x \in B} \|\text{grad } Q(x)\| \leq 3d \sup_{x \in B} |Q(x)|/R. \quad (+)$$

This is classical for  $n = 1$  and without any 3. Then the case  $n \geq 2$  follows by restricting  $Q$  to suitable disks in  $B$  (which bring along this unfortunate, and probably unnecessary 3). In fact, a similar inequality holds on every (convex) subset  $B \subset \mathbb{C}^n$  which contains “sufficiently many” “large” disks through every point.

And, (+) holds without 3 on the polydisk  $D(R) \times D(R) \times \cdots$  ( $n$  factors) as is seen by applying the 1-dimensional Bernstein lemma to circles in the



$n$  torus  $S^1(R) \times S^1(R) \times \cdots \times S^1(R)$ , making the *Shilov boundary* of the polydisk.

**(B'')** **Corollary:** *There is a point  $x \in B$  which is  $\varepsilon$ -far from the zero set  $Z$  of  $Q$  in  $B$  for some  $\varepsilon \geq R/3d$ , unless  $Q$  is identically zero.*

**Proof.** If the zero set  $Z$  is  $\varepsilon$ -dense in  $B$ , then clearly,

$$\sup_{x \in B} |Q(x)| \leq \varepsilon \sup_{x \in B} \| \text{grad } Q \|,$$

which makes  $\sup_{x \in B} |Q(x)| = 0$  for  $\varepsilon < R/3d$ , as follows from (+).

**Remarks:** (a) The above may stay true with  $\varepsilon \geq R/c\sqrt{d}$  (say for  $c = 1$ ). Of course, this is easy to prove with  $\varepsilon \geq R/c_n\sqrt{d}$  by evaluating the volume of the  $\varepsilon$ -neighborhood of  $Z \subset B$ ; the whole point, however, is to make the constants independent of the dimension! Actually the dimension free bound  $\varepsilon \geq R/c\sqrt{d}$  seems nontrivial even when  $Z$  is the union of  $d$  complex hyperplanes in  $\mathbb{C}$  intersected with  $B$ . (This special case gains in significance if we look at  $d$  hyperplanes in the Hilbert space  $\mathbb{C}^\infty$  and ask how dense they can be in  $B \subset \mathbb{C}^\infty$ ).

(b) Real polynomials  $Q$  also admit bounds on  $\| \text{grad } Q \|$  by  $|Q|$ , but now with the constant  $d^2$  (rather than  $d$ ) according to the *Markov inequality*. This gives a version of (B'') with  $\varepsilon \geq R/cd^2$  for real algebraic hypersurfaces in  $B = B(R)$  instead of the expected  $\varepsilon \geq R/cd$ . Getting this  $R/cd$  bound does not appear hard, since Markov's inequality is linear in  $d$  (deeply) inside  $B$ . In fact, every real algebraic subset  $Z$  in  $B$  of degree  $d$  and codimension  $k$  probably admits an  $\varepsilon$ -far point, with  $\varepsilon \geq R/cd^{1/k}$  (where  $c = 1$  is a possibility). One can slightly vary this conjecture by using different notions of degree. I would prefer the projective degree of the complexification of  $Z$ . But for the moment, I did not check this conjecture, even for unions of  $d$

planes intersected with  $B$ , where the case of real hyperplanes is relatively easy (see [Bang]). (One may ask in this regard how dense a union of linear subspaces and other simple subvarieties of finite codimension, such as spheres, can be in a given Banach space.) On the other hand, everything simplifies if one allows  $c$  to depend on the dimension (how boring!), where the bound with  $\varepsilon \geq R/c_n d^{1/k}$  is achieved by intersecting  $A$  with the standard grid of  $\varepsilon$ -cubes and applying the Petrovski–Thom–Milnor inequality (compare [Iva] and [Gro]Yom).

Finally, we point out a hard generalization of the nondensity properties of  $Z$  above to the nodal sets of eigenfunctions of differential operators, due to Donnelly and Fefferman.

**Proof of (B').** If  $k = \text{codim } X = 1$  and  $\ell = 0$ , then everything follows directly from ( $B''$ ) applied to suitable balls in affine charts in  $\mathbb{C}\mathbb{P}^n$ . Then we also get the case  $\ell = 0$  and arbitrary  $k$ , since every subvariety  $X$  of degree  $d$  is contained in a hypersurface  $X^*$  of degree  $d$ . Namely, one may take the cone  $X^*$  over  $X$  from some  $(k-2)$ -dimensional center, i.e., the pullback of the projection of  $X$  to some  $\mathbb{C}\mathbb{P}^{m+1}$ ,  $m = \dim X$ . Finally, one handles  $\ell = 1, 2, \dots$ , arguing by induction on  $\ell$  as follows. Take a point  $x_0 \in \mathbb{C}\mathbb{P}^0$   $\varepsilon_0$  far from  $X$  with  $\varepsilon_0 \approx d^{-1}$ , and project  $X$  to the opposite  $\mathbb{C}\mathbb{P}^{n-1}$ . The image  $X' \subset \mathbb{C}\mathbb{P}^{n-1}$  has degree  $d$  and so admits by the inductive hypothesis an  $(\ell-1)$ -plane  $\mathbb{C}\mathbb{P}^{\ell-1}$  lying  $\varepsilon'$ -far from it with  $\varepsilon' \geq (10d)^{-(\ell+1)}$ . Then the cone  $\mathbb{C}\mathbb{P}^\ell$  from  $x_0$  over  $\mathbb{C}\mathbb{P}^{\ell-1}$  lies as far from  $X$  as required if the implied constant in the relation  $\varepsilon \approx d^{-1}$  was suitably chosen (where the reader is left with the task of bringing the constants into line).

**Questions:** (a) What is the true dependence of  $\varepsilon_{\ell,d}$  on  $\ell$  and  $d$ ? Is  $\varepsilon_{\ell,d} \approx 1/d^{1/2(k-\ell)}$ ?

(b) What happens in the real algebraic case? What can one gain by looking for subvarieties of degree  $\delta \geq 2$  far from  $X$  instead of planes (where  $\delta = 1$ )?

**(C) Bound on dist by dist.** We denote by  $\text{dist}$  the standard  $(U(n+1)$ -invariant) metric on  $\mathbb{C}\mathbb{P}^n$  and by dist the metric on  $\mathbb{C}\mathbb{P}^m$  where we are interested in the behavior of the (degenerate) metrics on  $X \subset \mathbb{C}\mathbb{P}^n$ , where dist comes to  $X$  via the projection  $p$ . Since the center of  $p$  is  $\varepsilon$ -far from  $X$ , we trivially have

$$\underline{\text{dist}}|_X \leq c_\varepsilon \text{dist}|_X,$$

say for  $c_\varepsilon = 2\varepsilon^{-1}$ . (What is more interesting, one can also bound  $\text{dist}(x, x')$  in terms of dist( $p(x), p(x')$ ) for all  $x \in X$  and  $x' \in \Sigma \subset X$ , independently

of  $m$ , as will become clear later on.)

**(D) Comparison between  $\underline{\text{dist}}$  and  $\underline{\text{DIST}}$ .** We denote by  $\underline{\text{DIST}}$  the path metric on  $X$  induced from  $\underline{\text{dist}}$  by our  $p: X \rightarrow \mathbb{C}\mathbb{P}^m$ . This is indeed a true metric, since the map  $p$  is finite-to-one, as follows from the fact that the center of the projection does not meet  $X$ . It is obvious that

$$\underline{\text{dist}} \leq \underline{\text{DIST}},$$

where  $\underline{\text{dist}}(x, x') \stackrel{\text{def}}{=} \underline{\text{dist}}(p(x), p(x'))$ . Somewhat surprisingly, we also have the following

**(D') Partial equality between  $\underline{\text{DIST}}$  and  $\underline{\text{dist}}$ .** We have

$$\underline{\text{DIST}}(x, x') = \underline{\text{dist}}(x, x')$$

for all  $x \in X$  and  $x' \in \Sigma = \Sigma(p)$ .

**Proof.** Join  $p(x)$  with  $p(x')$  by the shortest geodesic arc  $a$  in  $\mathbb{C}\mathbb{P}^m$  and observe that there is a *covering arc*  $A$  in  $X$  issuing from  $x$ . Indeed, our arc  $a$  lies in some complex line  $\mathbb{C}\mathbb{P}^1 \subset \mathbb{C}\mathbb{P}^n$ , and the covering  $A$  should be constructed in the algebraic curve  $X^1 = X \cap p^{-1}(\mathbb{C}\mathbb{P}^1)$ , which goes to  $\mathbb{C}\mathbb{P}^1$  by the map  $p|_{X^1}: X^1 \rightarrow \mathbb{C}\mathbb{P}^1$ . Since  $\dim_{\mathbb{C}} X^1 = 1$  and since  $p$  is finite-to-one, the map  $p|_{X^1}: X^1 \rightarrow \mathbb{C}\mathbb{P}^1$  is a covering away from finitely many ramification points, where  $p$  is locally modeled by  $z \mapsto z^r$  in the complex plane  $\mathbb{C}$  (with possible values  $r = 2, 3, \dots, d$ ), provided that the curve  $X^1$  is irreducible. If it is reducible, then this (ramification) behavior refers to each irreducible branch of  $X^1$ . It is obvious that the map  $z \mapsto z^r$  has the path lifting property (at least for piece-wise smooth paths in  $\mathbb{C}$ ), which yields the desired lifts for  $X^1 \rightarrow \mathbb{C}\mathbb{P}^1$ .

The path  $A$  starting from  $x$  terminates at some point in  $X$  over  $p(x')$ , and since  $p$  is one-to-one over  $\Sigma \ni x'$ , the path  $A$  terminates at  $x'$ , as this is the only point over  $p(x')$ . It follows that  $\underline{\text{DIST}}(x, x') \leq \text{length}(A) = \text{length}(a) = \underline{\text{dist}}(x, x')$ .

**Remarks.** (a) The path lifting property is shared by all proper surjective holomorphic maps between irreducible complex analytic varieties. In fact, we can lift (real analytic) arcs also for real analytic maps which have *no folds* as a simple (and well-known, I guess) argument shows. The reader is invited to think the matter through for him/herself.

(b) If  $\Sigma$  is nonempty, then the above implies that

$$\text{diam}(X, \underline{\text{DIST}}) \leq 2 \text{diam}(\mathbb{C}\mathbb{P}^m) = 2\pi.$$

(This was pointed out to me by Carlos Simpson.)

**(E) Bound on DIST by DIST.** Here DIST stands for the induced path metric in  $X \subset \mathbb{C}\mathbf{P}^n$  which obviously bounds DIST in terms of our  $\varepsilon = \varepsilon_{k-1,d} > 0$  by

$$\underline{\text{DIST}} \leq 2\varepsilon^{-1} \text{DIST}.$$

It follows by a simple compactness argument that

$$\text{DIST} \leq \rho(\underline{\text{DIST}}) \tag{*}$$

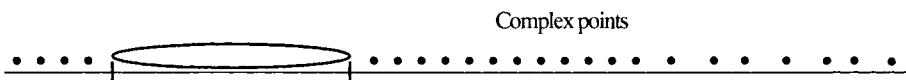
for some function  $\rho = \rho_{d,k,m}$  satisfying  $\rho(\delta) \rightarrow 0$  for  $\delta \rightarrow 0$ . Since DIST is determined by (the length of) arcs contained in projective lines in  $\mathbb{C}\mathbf{P}^m$ , we can bound  $\rho_{d,k,m} \leq \rho_{d,k,t} = \rho_{d,k}$ , thus making (\*) independent of  $m$ .

Here is a more specific (rather rough) bound on  $\rho$ .

$$\rho(\delta) \leq \text{const } d^{2k+2} \delta^{1/d} \tag{★}$$

for some const  $\leq 1,000,000$ .

**Idea of the proof.** We must show that paths do not become much longer as they are lifted from  $\mathbb{C}\mathbf{P}^m$  to  $X \subset \mathbb{C}\mathbf{P}^n$  for the projection  $p: X \rightarrow \mathbb{C}\mathbf{P}^m$ . As we mentioned before, this lift takes place over complex projective lines in  $\mathbb{C}\mathbf{P}^m$ , and so we may assume that  $m = 1$  to start with. If a  $\delta$ -short arc  $a$  in  $\mathbb{C}\mathbf{P}^1$  becomes long in  $X$ , where we assume for the moment that  $n = 2$ , then  $X$  lies  $\delta$ -close to some projective line  $L \subset \mathbb{C}\mathbf{P}^2$  issuing from the center (which is  $\varepsilon$ -far away from  $X$ ). In fact,  $X$  and  $L$  are mutually close along some real algebraic arc  $A$  of degree  $d$  and length  $\rho$ , and by an interpolation argument (see below),  $L$  must be everywhere close to  $X$  if  $\rho$  is large compared to  $\varepsilon$ . Notice that this is a purely *complex* algebraic phenomenon: an ellipse can be close to a line along a segment without approaching this line outside this segment in the *real* domain.



This happens because a *real* polynomial may be small at some point without vanishing near this point. In the complex domain, however, we have the following standard

**(E') Vanishing lemma:** Let  $Q$  be a nonconstant polynomial of degree  $d$  on the  $R$ -ball  $B = B(x_0, R) \subset \mathbb{C}^n$  with  $\sup_{x \in B} |Q(x)| \geq b$ . If  $|Q(x_0)| \leq \delta_0$

at the center  $x_0$  of  $B$ , then the distance  $\varepsilon = \text{dist}(x_0, Z)$  from  $x_0$  to the zero set  $Z$  of  $Q$  is bounded by

$$\frac{\varepsilon}{1 + R^{-1}\varepsilon} \leq R \left( \frac{\delta_0}{b} \right)^{1/d}.$$

**Proof.** Everything trivially reduces to the case  $n = 1$ ,  $x_0 = 0 \in \mathbb{C}$ ,  $R = 1$ , and where the polynomial  $Q(x)$  decomposes as the product over its roots  $z_i \in \mathbb{C}$ . Thus,

$$\left| \frac{b}{\delta_0} \right| = \sup_{|x| \leq 1} \left| \prod_{i=1}^d \left( 1 - \frac{x}{z_i} \right) \right| \leq \left( 1 + \frac{1}{\delta} \right)^d,$$

for  $\delta = \min_{i=1, \dots, d} |z_i|$ .

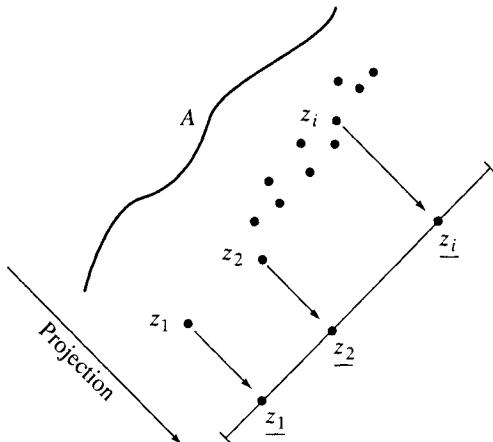
Next, we need another elementary and well-known

(E'') **Interpolation lemma:** Let  $A \subset B = B(x_0, R) \subset \mathbb{C}$  be a connected set (arc) of diameter  $\geq \rho_0$ . Then

$$b \stackrel{\text{def}}{=} \sup_{x \in B} |Q(x)| \leq b_0 (CR/\rho_0)^d$$

for  $b_0 \stackrel{\text{def}}{=} \sup_{x \in A} |Q(x)|$ , where  $Q(x)$  is as before an arbitrary polynomial on  $\mathbb{C}$  of degree  $\leq d$  and  $C$  is a numerical constant  $\leq 20$ .

**Proof.** Assume  $B = B(0, 1)$  and  $Q(x) = \prod_{i=1}^d (x - z_i)$ . Then normally project  $A$  onto some segment  $I \subset B$  of length  $\rho_0$  and integrate  $\sum_{i=1}^d \log |\underline{x} - \underline{z}_i|$  over  $\underline{x} \in I$ , where  $\underline{z}_i \in I$  are the projections of  $z_i$ .



Since  $\log x$  is integrable at zero, we have

$$\int_I \sum_{i=1}^d \log |\underline{x} - \underline{z}_i| d\underline{x} \leq d \text{const},$$

and consequently,

$$\sup_{x \in A} \prod_{i=1}^d |x - z_i| \geq (\rho_0 / \text{const})^d.$$

If  $|z_i| \leq 2$  for all  $i = 1, \dots, d$ , then obviously  $\sup_{x \in B} |Q(x)| \leq 4^d$  and the proof follows. Otherwise, apply the above to the partial product  $Q_\bullet$  as the remaining factor  $Q^\bullet = Q/Q_\bullet = \prod_{|z_i| > 2} (x - z_i)$  obviously satisfies

$$\sup_{x \in B} |Q^\bullet(x)| \leq 4^d \inf_{x \in A} |Q^\bullet(x)|.$$

**Proof of (★) in (E).** Start with the case  $k = 1$  and look at our lifted arc  $A \subset X \subset \mathbb{CP}^2$  issuing from a point  $x_0 \in X$  and projecting to a  $\delta$ -segment in  $\mathbb{CP}^1$ . We shall work in a suitable affine chart  $\mathbb{C}^2 \subset \mathbb{CP}^2$  with the origin at the center of the projection  $c_0 \in \mathbb{CP}^2$ , such that  $A$  lies inside the unit ball  $B = B(0, 1) \subset \mathbb{C}^2 \subset \mathbb{CP}^2$ , and let  $B' = B \cap L$  for the (projecting) line  $L$  between  $c_0$  and  $x_0$ . We normally project  $A$  to  $L$ , call the image  $A' \subset L$  and observe that  $A' \subset B'$  and that the diameter of  $A'$  is  $\geq \rho_0 \geq \rho/10d$  for  $p = \text{length } A$ . In fact, the length of a piece of a real algebraic curve of degree  $d$  in  $\mathbb{C}^2 = \mathbb{R}^4$  is bounded by its diameter

$$\text{length} \leq d \text{const} \cdot \text{diameter}$$

according to the Buffon–Crofton formula expressing the length as the integrated intersection number of the curve with the hyperplanes in  $\mathbb{R}^4$ .

We observe that  $A'$  lies  $(5\varepsilon^{-1}\delta)$ -close to  $X$  and, therefore,

$$\sup_{x \in A'} |Q(x)| \leq \text{const} \cdot \varepsilon^{-1} \delta$$

by the Bernstein inequality, where  $Q$  is the polynomial defining  $X$  in  $\mathbb{C}^2$  normalized to have the sup-norm equal 1 on the ball  $B \subset \mathbb{C}^2$ . Then the interpolation lemma applies to  $A' \subset B' \subset L = \mathbb{C}$  and yields the following bound on  $Q$  on  $B'$ ,

$$\sup_{x \in B'} |Q(x)| \leq C_1^d d \varepsilon^{-1} \delta / \rho_0^d,$$

and the vanishing bounds the distance  $\varepsilon$  from  $c_0$  to  $X$  by

$$\varepsilon \leq C_2(d/\varepsilon^{-1}\delta) \varepsilon^{1/d} / \rho_0.$$

Since  $\varepsilon \geq 1/10d$  by (B') applied to  $\ell = 0$ , we conclude that

$$\rho_0 \leq C_3 d^{1+2/d} \delta^{1/d}$$

and thus

$$\rho \leq C_4 d^{2+2/d} \delta^{1/d}$$

for  $C_4 \leq 100000$ . This settles  $(\star)$  for  $k = 1$ , and now we turn to the general case of  $k \geq 2$ . We project  $X$  to  $k$  mutually perpendicular planes, say  $\mathbb{C}\mathbb{P}_i^2$ ,  $i = 1, \dots, k$ , passing through  $\mathbb{C}\mathbb{P}^1$ , and apply the above to each curve  $X_i \subset \mathbb{C}\mathbb{P}_i^2$  projected to  $\mathbb{C}\mathbb{P}^1 = \bigcap_{i=1}^k \mathbb{C}\mathbb{P}_i^2$  from the center  $c_i = \mathbb{C}\mathbb{P}^{k-1} \cap \mathbb{C}\mathbb{P}_i^2$ , where  $\mathbb{C}\mathbb{P}^{k-1}$  is the center of the projection  $p: X \rightarrow \mathbb{C}\mathbb{P}^1$ . Clearly,

$$\varepsilon_i \stackrel{\text{def}}{=} \text{dist}(c_i, X_i) \geq \varepsilon = \text{dist}(\mathbb{C}\mathbb{P}^{k-1}, X),$$

and so we bound each  $\text{DIST}_i$  of  $X_i$  in  $\mathbb{C}\mathbb{P}^2$  by the formula above, with  $\varepsilon = (10d)^{-k}$  (see (B)), which makes  $\rho_i \leq C_4 d^{((k+1)d+1)/d} \delta^{1/d}$ . On the other hand, the metric  $\text{DIST}$  on  $X$  is easily bounded by  $\varepsilon^{-1} \sum_{i=1}^k \text{DIST}_i$  on  $X \rightarrow X_i \subset \mathbb{C}\mathbb{P}_i^2$ , and so we get the desired bound

$$\rho(\delta) \leq \text{const } d^{2k+1+d^{-1}} \delta^{1/d},$$

which yields  $(\star)$ .

**Remark:** The  $\delta^{1/d}$ -term in  $(\star)$  is right, as seen for the map  $x \mapsto x^d$ , but  $d^{2k+\dots}$  looks excessive. A better estimate may be expected with a suitable *Schwartz lemma* for the embedding  $(X, \text{DIST}) \hookrightarrow \mathbb{C}\mathbb{P}^n$ . Actually, the worst example I see right now is the curve given in affine coordinates  $x_0, \dots, x_k$  by the equations  $x_i^d = x_0$ ,  $i = 1, \dots, k$ , projected by  $(x_0, \dots, x_k) \mapsto x_0$ , where  $\rho(\delta) \approx \sqrt{k} \delta^{1/d}$  near  $x_0 = x_1 = \dots = x_k = 0$ .

**(F) Partial bound on the path metric  $\text{DIST}$  on  $X \subset \mathbb{C}\mathbb{P}^n$  by  $\text{dist}_{\mathbb{C}\mathbb{P}^n}$ .** We just combine (B)-(E) and arrive at the estimate

$$\text{DIST}(x, x') \leq C_{k,d} (\text{dist}(x, x'))^{1/d} \tag{**}$$

for all  $x \in X$  and  $x' \in \Sigma$ , where  $\Sigma$  with  $\text{codim } \Sigma = d - 1$  is the maximal multiplicity locus of the projection  $X \rightarrow \mathbb{C}\mathbb{P}^m$ ,  $m = \dim X$ , from a suitable ( $\varepsilon$ -far away from  $X$  with  $\varepsilon \geq (10d)^{-k}$ ) center  $\mathbb{C}\mathbb{P}^{k+1} \subset \mathbb{C}\mathbb{P}^n$ , and

$$C_{k,d} \leq \text{const } d^{3k+2},$$

$$\text{const} \leq 10^9.$$

**(G) Evaluation of  $\text{ObsDiam}(X)$  with respect to  $\text{DIST}$ .** Take an  $\varepsilon$ -neighborhood  $U_\varepsilon(\Sigma) \subset \mathbb{C}\mathbb{P}^n$  and show that  $U_\varepsilon(\Sigma) \cap X$  contains much of the

measure of  $X$  (see below). Then the concentration for  $(X, \text{dist})$  applied to the part of  $X$  in  $U_\varepsilon(\Sigma)$ , yields via  $(\star)$  a similar (albeit weaker) concentration for  $(X, \text{DIST})$ . Here are the details.

**(G') Lemma:** *Let  $X$  and  $Y \subset X$  be complex algebraic subvarieties in  $\mathbb{C}\mathbb{P}^n$  of codimensions  $k$  and  $\ell \geq k$  correspondingly, with normalized Riemannian measures (volumes). Then*

$$\mu_X(X \cap U_\varepsilon(Y)) \geq 1 - \frac{8}{\varepsilon} e^{-\varepsilon^2 n / 72\ell}.$$

**Proof.** Let  $\kappa$  denote the  $\mu_X$ -measure of the complement  $X_0 = X \setminus U_\varepsilon(Y)$  and observe that the neighborhoods  $U_{\varepsilon_0}(X_0)$  and  $U_{\varepsilon_1}(Y)$  in  $\mathbb{C}\mathbb{P}^n$  may intersect only at their boundaries for  $\varepsilon_0 + \varepsilon_1 = \varepsilon$ , and so the sum of their measures  $\mu = \mu_{\mathbb{C}\mathbb{P}^n}$  does not exceed  $1 = \mu(\mathbb{C}\mathbb{P}^n)$ . On the other hand, the  $\mu$ -measures of these neighborhoods can be bounded from below according to  $(\star)$  in 3½.28 or rather by the  $\mathbb{C}\mathbb{P}^n$ -version of that inequality. Namely,

$$\mu(U_{\varepsilon_0}(X_0)) \geq b_{\mathbb{C}}(k, \varepsilon_0)\kappa \quad (\star)_C$$

and

$$\mu(U_{\varepsilon_1}(Y)) \geq b_{\mathbb{C}}(\ell, \varepsilon_1) \quad (\star)'_C$$

where  $b_{\mathbb{C}}(k, \varepsilon_0)$  denotes the measure of the  $\varepsilon$ -ball in  $\mathbb{C}\mathbb{P}^k$  with the normalized measure. These inequalities are rather weak as they stand, but their power is enhanced by the concentration property of  $\mathbb{C}\mathbb{P}^n$ , which is at least as good as that of  $S^{2n-1}$ , which Lipschitz dominates  $\mathbb{C}\mathbb{P}^n$  via the Hopf map  $S^{2n-1} \rightarrow \mathbb{C}\mathbb{P}^n$  (compare [Milm]APF, [Milm]HPL, and [Mil–Sch]). This concentration tells us that the  $\delta$ -neighborhood of a subset  $U \subset \mathbb{C}\mathbb{P}^n$  of measure  $\mu_0$  dramatically (even exponentially) increases with  $\delta$ . This suggests looking at  $U_{\varepsilon_0}(X_0)$  as  $U_{\varepsilon'_0}(U_{\varepsilon''_0}(X_0))$  for suitable  $\varepsilon'_0$  and  $\varepsilon''_0$  with  $\varepsilon'_0 + \varepsilon''_0 = \varepsilon_0$ , and similarly to think of  $U_{\varepsilon_1}(Y)$ . More technically, we use the bound on the (separation) distance between two subsets  $U_0$  and  $U_1$  of measure  $\geq \kappa'$ ,  $\text{dist}(U_0, U_1) \leq d(\kappa') = -\text{ObsDiam}(\mathbb{C}\mathbb{P}^n, -\kappa') \leq \text{ObsDiam}(S^{2n-1}, \kappa')$  (see 3½.F). We apply this to the neighborhoods  $U_0 = U_{\varepsilon'_0}(X_0)$  and  $U_1 = U_{\varepsilon'_1}(Y)$ , which satisfy

$$\text{dist}(U_0, U_1) \geq d' = \varepsilon''_0 + \varepsilon''_1 = \varepsilon - \varepsilon'_0 - \varepsilon'_1,$$

and

$$\begin{aligned} \mu(U_0) \geq \mu_0 &= b_{\mathbb{C}}(k, \varepsilon'_0)\kappa, \\ \mu(U_1) \geq \mu_1 &= b_{\mathbb{C}}(\ell, \varepsilon'_1). \end{aligned}$$

We invoke the rough (and obvious) lower bound

$$b_{\mathbb{C}}(k, \varepsilon) \geq \left(\frac{\varepsilon}{4}\right)^{2k}$$

for  $\varepsilon \leq 1$ , set  $\kappa' = \min((\kappa\varepsilon'_0/4)^{2k}, (\varepsilon'_1/4)^{2\ell})$ , and combine the above with the Levy inequality (see 3½.19)

$$d' \leq d(\kappa') \leq \frac{3}{\sqrt{n}} \sqrt{-\log(\kappa'/2)},$$

with  $3/\sqrt{n} \geq 2\sqrt{2}/\sqrt{2n-1}$  since we care little for exact numbers). We choose  $d' = \varepsilon/2$  and obtain

$$\frac{\varepsilon}{2} \leq \frac{3}{\sqrt{n}} \min \left( \sqrt{-2k \log(\varepsilon'_0/4)\kappa}, \sqrt{-2\ell \log(\varepsilon'_1/4)} \right),$$

where we are free to choose any  $\varepsilon'_0$  and  $\varepsilon'_1$  satisfying  $\varepsilon'_0 + \varepsilon'_1 = \varepsilon/2$ . Being lazy, we stick to  $\varepsilon'_0 = \varepsilon'_1 = \varepsilon/4$  and conclude that

$$\frac{\varepsilon}{2} \leq \frac{3}{\sqrt{n}} \sqrt{-2\ell \log(\varepsilon\kappa/8)},$$

keeping in mind that  $\ell \geq k$  and  $\kappa \leq 1$ . Thus,

$$\kappa \leq \frac{8}{\varepsilon} e^{-\varepsilon^2 n / 72\ell}.$$

**(G'')** **Evaluation of ObsDiam( $\Sigma$ ) for DIST| $\Sigma$ .** We know (see 3½.28) that

$$\text{ObsDiam}(\Sigma, -\kappa)_{\text{dist}} \leq 10 \sqrt{\frac{\ell}{n}} \sqrt{-\log \frac{\ell}{n} \kappa}$$

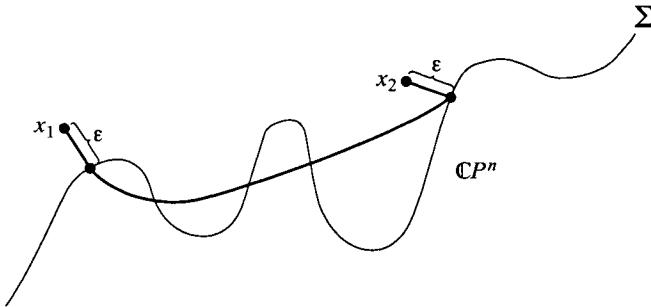
for  $\ell = \text{codim}(\Sigma = \mathbb{C}\text{P}^n) \leq k + d$  (where  $k = \dim X$  and  $d = \deg X$ ). This combines with the (\*\*) above and yields

$$\begin{aligned} \text{ObsDiam}(\Sigma)_{\text{DIST}} &\leq C_{k,d} (\text{ObsDiam}(\Sigma)_{\text{dist}})^{1/d} \\ &\leq 10^{11} d^{3k+2} \left(\frac{\ell}{n}\right)^{1/2d} (-\log \frac{\ell}{n} \kappa))^{1/2d}. \end{aligned}$$

In particular, for fixed  $k, d$ , and  $n \rightarrow \infty$ ,

$$\text{ObsDiam}(\Sigma)_{\text{DIST}} \leq n^{-1/2d+\alpha_n}$$

for some  $\alpha_n \rightarrow 0$  as  $n \rightarrow \infty$ .



(G'') At last we bring everything together and evaluate  $\text{ObsDiam}(X)_{\text{DIST}}$  by looking at  $U_\varepsilon(\Sigma) \cap X \subset X$  and arguing as above. First, we observe with (★) that the metric DIST on  $U_\varepsilon(\Sigma)$  is bounded by

$$\text{DIST}(x_1, x_2) \leq C_{k,d}((\text{dist} + 2\varepsilon)^{1/d} + 2\varepsilon^{1/d})$$

via the triangle inequality.

It follows that

$$\text{ObsDiam}(U_\varepsilon(\Sigma), -\kappa)_{\text{DIST}} \leq 2C_{k,d}((\text{ObsDiam}(U_\varepsilon(\Sigma); -\kappa)_{\text{dist}} + 2\varepsilon)^{1/d} + 2\varepsilon^{1/d}),$$

which should be combined with the obvious inequalities

$$\text{ObsDiam}(U_\varepsilon(\Sigma), -\kappa)_{\text{dist}} \leq \text{ObsDiam}(X, -\kappa)_{\text{dist}}$$

and

$$\text{ObsDiam}(X, -\kappa - \kappa_\varepsilon)_{\text{DIST}} \leq \text{ObsDiam}(U_\varepsilon(\Sigma), \kappa)_{\text{DIST}}$$

for  $\kappa_\varepsilon = \mu_X(X \setminus U_\varepsilon(\Sigma))$ . We then use our bound

$$\text{ObsDiam}(X; -\kappa)_{\text{dist}} \leq 10 \left( -\frac{k}{n} \log \left( \frac{k}{n} \kappa \right) \right)^{1/2} \leq 10 \left( -\frac{\ell}{n} \log \left( \frac{k}{n} \kappa \right) \right)^{1/2}$$

from 3 1/2.28 and the inequality  $\kappa_\varepsilon \leq 8/\varepsilon e^{-\varepsilon^2 n/72\ell}$  in (G'). Next, we apply all these inequalities to  $\varepsilon = \varepsilon_x = 10(-(\ell/n) \log(k\kappa/n))^{1/2}$ . Then we have

$$\text{ObsDiam}(X, -\kappa - \kappa_\varepsilon)_{\text{DIST}} \leq 100C_{k,d} \left( \frac{\ell}{n} \right)^{1/2d} \left( -\log \left( \frac{k}{n} \kappa \right) \right)^{1/2d}$$

for

$$\begin{aligned} \kappa_\varepsilon &\leq \left( -\frac{\ell}{n} \log \left( \frac{k}{n} \kappa \right) \right)^{-1/2} \exp \frac{n}{\ell} \left( \frac{\ell}{n} \right)^{1/2d} \log \left( \frac{k}{n} \kappa \right) \\ &= \kappa (k/\ell n)^{1/2} / (-\log((k/n)\kappa))^{1/2}. \end{aligned}$$

This implies  $\kappa_\varepsilon \leq \kappa$  for  $\kappa \geq ne^{-n}$  and consequently,

$$\text{ObsDiam}(X, -\kappa)_{\text{DIST}} \leq 100C_{k,d} \left( \frac{\ell}{n} \right)^{1/2d} (-\log(k\kappa/n))^{1/2d}$$

for all  $n$  and  $\kappa \geq 2ne^{-n}$ , where  $\ell \leq k(d-1)$  and  $C_{k,d} \leq 10^9 d^{3k+2}$ .

So, the final bound on the observable diameter of a complex algebraic submanifold  $X \subset \mathbb{CP}^n$  of codimension  $k$  and degree  $d$  and normalized Riemannian volume with the induced path metric reads

$$\text{ObsDiam}(X, -\kappa) \leq 10^{11} d^{3k+2} \left( \frac{k(d-1) \log(2n/k\kappa)}{n} \right)^{1/2d} \quad (**)$$

provided that  $\kappa \geq 2ne^{-n}$ . This makes

$$\text{ObsDiam}(X) \leq \text{const} \cdot \left( \frac{\log n}{n} \right)^{1/2d}$$

for fixed  $k, d, \kappa$ , and  $n \rightarrow \infty$ .

**(H) Remarks, exercises, and open problems.** (a) Our argument can probably be improved to eliminate  $\log n$  from the above estimate, but it is less clear whether the exponent  $1/2d$  is to the point and what the right coefficient instead of  $d^{3k+2}$  should be. (It is highly unlikely that one can get a true insight into the asymptotic measure-theoretic geometry of algebraic varieties  $X$  with an argument similar to ours, since all we do is compare  $X$  with  $\mathbb{CP}^n$  based on a partial majorization of  $X$  by  $\mathbb{CP}^n$  without studying  $X$  at a closer range. But it may be useful to axiomatize our approach, which we leave to the pleasure of the reader.)

(b) *The ordinary diameter of  $(X, \text{DIST})$  is bounded by*

$$\text{diam}(X, \text{DIST}) \leq 10d$$

*for every connected complex algebraic subvariety in  $\mathbb{CP}^n$  of degree  $d$ .*

**Proof.** If  $\dim_{\mathbb{C}} X = 1$ , then the area of  $X$  equals  $d$  if we normalize the Kähler form (metric)  $\omega$  in  $\mathbb{CP}^n$  by  $\int_{\mathbb{CP}^1} \omega = 1$ . On the other hand, the unit disks in  $(X, \text{DIST})$  have areas  $\geq \text{const} > 1/5$  (see (e) below). This settles the matter for curves  $X \subset \mathbb{CP}^n$  and the general case follows from the following obvious

(b<sub>1</sub>) **Lemma:** *For every irreducible  $X \subset \mathbb{CP}^n$  of codimension  $k$  and every pair of points  $x_0, x \in X$ , there exists a  $(k+1)$ -plane in  $\mathbb{CP}^n$  passing through*

$x_0$  such that the irreducible component of the intersection  $X \cap P$  containing  $x_0$  also contains  $x$ .

(b<sub>2</sub>) **Exercise.** Render the above argument *real* algebraic.

(b<sub>3</sub>) What is the actual range of the function  $X \mapsto \text{diam}(X, \text{DIST})$  for  $X$  running over the subvarieties in  $\mathbb{C}\mathbb{P}^n$  of given degree and dimension? Sid Frankel suggested that these diameters of curves in  $\mathbb{C}\mathbb{P}^2$  are bounded by a constant *independent of the degree*, but F. Bogomolov constructed a counterexample, i.e., a sequence of complex algebraic curves  $X_i \subset \mathbb{C}\mathbb{P}^2$  with  $\text{diam}(X_i, \text{DIST}) \rightarrow \infty$ . Nevertheless, it is still conceivable that a universal bound exists for hypersurfaces in  $\mathbb{C}\mathbb{P}^n$  for  $n \geq 3$ . Similarly, one wonders what the range of the function  $X \mapsto \text{ObsDiam}(X, -\kappa)\text{DIST}$  is for the  $X$  above. Does it truly depend on  $\deg X$ ?

(c) The examples of functions  $\text{diam}$  and  $\text{ObsDiam}$  on the spaces of algebraic subvarieties in  $\mathbb{C}\mathbb{P}^n$  (or in any given ambient algebraic space for this matter) suggest a more general view on the structure of various geometric functions on the space of  $X$ 's. To be specific, stick to hypersurfaces  $X$  in  $\mathbb{C}\mathbb{P}^n$  of degree  $d$ , where eventually  $n, d \rightarrow \infty$ . Such hypersurfaces themselves constitute a projective space  $\mathcal{X} = \mathbb{C}\mathbb{P}^N$ ,  $N = (n+d)!/n!d! - 1$ , which is highly concentrated for large  $d$  and/or  $n$ , and each “natural geometric function”  $X \mapsto \text{Inv}(X)$  should be strongly localized near a single value.

Among such functions (maps), one may distinguish certain universal ones such as the tautological map from  $\mathcal{X} = \mathbb{C}\mathbb{P}^N$  to the space of subsets  $X \subset \mathbb{C}\mathbb{P}^n$  with the Hausdorff metric, or to the space of measures on  $\mathbb{C}\mathbb{P}^n$ , where each  $X$  goes to the (normalized) Riemannian measure supported on  $X \subset \mathbb{C}\mathbb{P}^n$ .

(d) The “natural functions” are equally interesting in the real case, say on the space of real algebraic hypersurfaces  $X \subset \mathbb{R}\mathbb{P}^n$  of degree  $d$ . Here, one has several new possibilities, such as  $X \mapsto \text{vol}_{n-1}(X)$  and  $X \mapsto (\text{number of components of } X)$ , where the latter is accompanied by further topological invariants of  $X$ , such as the Betti numbers, the characteristic numbers, etc. For example, if  $n = 1$  and  $\dim X = 0$ , then the basic invariant is the cardinality of  $X$ , and the question is to determine the measures of  $\mathcal{X}_i = \{X \subset \mathcal{X} = \mathbb{R}\mathbb{P}^d : \text{card } X = i\}_{i=0, \dots, d}$  or rather the asymptotic behavior for  $d \rightarrow \infty$  of some functions of  $\mu(\mathcal{X}_i)$ .

(d<sub>1</sub>) **Exercise:** Consider the Veronese curve  $V_1 \subset \mathbb{R}\mathbb{P}^d$  that is the image of the Veronese embedding  $\mathbb{R}\mathbb{P}^1 \rightarrow \mathbb{R}\mathbb{P}^d$  for  $(t_1, t_2) \mapsto (t_1^d, t_1^{d-1}t_2, \dots, t_2^d)$  in

homogeneous coordinates, and observe that the 0-dimensional subvarieties  $X$  in  $\mathbb{R}P^1$  given by the homogeneous equations

$$c_0 t_1^d + c_1 t_1^{d-1} t_2 + \cdots + c_d t_2^d = 0$$

correspond to the hyperplanes  $H$  in  $\mathbb{C}P^d$  given by the equations  $c_0 x_0 + c_1 x_1 + \cdots + c_d x_d = 0$ , where  $X = V^1 \cap H \subset V^1 = \mathbb{C}P^1$ . Evaluate  $\text{length}(V)$  in  $\mathbb{C}P^d$ , identify this using Crofton's formula with the average cardinality of  $X$ , that is,

$$\int_{\mathcal{X}} \text{card } X \, dX = \int_{\mathcal{H}} (V^1 \cap H) \, dH$$

for  $\mathcal{X} = \mathcal{H} = \mathbb{C}P^d$  (where  $\mathcal{H}$  appears as the projective space of the hyperplanes  $H$  in the space  $\mathbb{C}P^d$  containing  $V^1$ ) and study the asymptotic behavior of this  $\text{length}(V^1) = \int \text{card}(X) \, dX$  for  $d \rightarrow \infty$ . Then show that the average number of roots of a random real polynomial of degree  $d$  grows approximately as  $\log d$  (compare Ch. 1 in [Kac]).

Next, define the Veronese map  $\mathbb{R}P^n \rightarrow \mathbb{R}P^N$ ,  $N = (n+d)!/n!d! - 1$ , try to evaluate the  $n$ -dimensional volume and the total curvature of the Veronese image  $V^n = \mathbb{R}P^n$  in  $\mathbb{R}P^N$ , and estimate the average Euler characteristic

$$\int_{\mathcal{X}} \chi(X) \, dX = \int_{\mathcal{H}} \chi(V^n \cap H) \, dH,$$

where  $\mathcal{X} = \mathcal{H} = \mathbb{R}P^N$ . (I admit, I did not try it myself; the reader is encouraged to study the work by Smale and Shub on the complexity of solutions of algebraic equations, especially their papers Bezout I. – Bezout V).

**Question:** How strongly does the Euler characteristic (function)  $X \mapsto \chi(X)$  concentrate near its mean value? (Also one wonders how strongly concentrated the average estimates in [Sma–Shu]BI–BV are.)

(e) Let  $X \subset \mathbb{C}P^n$  and  $Y \subset X$  be complex algebraic varieties of dimensions  $m$  and  $n$ , respectively. Is the  $2m$ -volume of the intersection  $X \cap U_\varepsilon(Y) \subset X$  bounded from below by  $\text{vol } U_\varepsilon(\mathbb{C}P^r)$  in  $\mathbb{C}P^m$ ? This question makes sense for the  $\varepsilon$ -neighborhoods in  $X$  with respect to the metrics dist (induced from  $\mathbb{C}P^n$ ) and DIST (corresponding to the induced path metric in  $X$ ), where the latter question seems significantly harder. For example, if  $r = \dim Y = 0$ , then the *sharp* lower bound on the volume of  $U_\varepsilon(Y) = B(\varepsilon) \subset X$  for dist follows from the standard monotonicity formula for minimal subvarieties in  $\mathbb{C}P^n$  (Lelong inequality), but the similar sharp lower bound for the volumes of DIST-balls is probably still unsettled. In fact, one expects that every

small domain  $U \subset X$  satisfies the *sharp isoperimetric inequality*

$$\text{vol}_{2m}(U) \leq C_m I_m(\text{vol}_{2m-1} \partial U),$$

where  $I_m(s)$  denotes the volume of the ball  $B$  in  $\mathbb{C}\mathbb{P}^m$  with  $\text{vol}_{2m-1}(B) = s$ . Such an inequality (which rather easily implies the lower bounds on the volume of DIST-balls  $B(\varepsilon)$  in  $X$  when applied to the concentric balls  $B(t\varepsilon)$ ,  $t \in [0, 1]$ ) is known to hold for (domains in) *all minimal subvarieties* in  $\mathbb{C}^n = \mathbb{R}^{2n}$  (this is highly nontrivial, see [Alm]Iso), and it yields some information on small domains  $U \subset X \subset \mathbb{C}\mathbb{P}^n$  via suitable weakly distorting holomorphic diffeomorphisms of small Euclidean balls  $B(\varepsilon) \subset \mathbb{C}^n$  to  $\mathbb{C}\mathbb{P}^n$  (local Kähler coordinates in  $\mathbb{C}\mathbb{P}^n$ ).

One can specify the question above to  $Y = X \cap H$  for a hyperplane  $H \subset \mathbb{C}\mathbb{P}^n$  and then inquire further into the measure-theoretic shape of the function  $H \mapsto \text{vol}_{2m}(U_\varepsilon(X \cap H))$  for  $H$  running over the space  $\mathcal{H} = \mathbb{C}\mathbb{P}^n$ . Actually, one may move  $Y$  in a wider class of subvarieties in  $X$ , i.e., one still expects the sharp lower bound on  $\text{vol}_m(U_\varepsilon(Y))$  in  $X$  for every  $(2m - 2)$ -cycle  $Y$  in  $X$  homologous to  $X \cap H$  in  $X$  without any holomorphicity condition on  $Y$ . But this question remains open, even for  $\mathbb{C}\mathbb{P}^n$ !

Finally, we observe that one has (sharp) lower bounds on the volumes of certain subvarieties in some (often homogeneous or locally homogeneous) spaces (e.g., obtained with *calibrating forms* of Harvey and Lawson) one expects similar bounds on the  $\varepsilon$ -neighborhoods of these submanifolds. For example, one expects that the  $\varepsilon$ -neighborhood of every  $r$ -dimensional subvariety  $Y$  nonhomologous to zero in a real, complex, or quaternionic projective space  $X$  has  $\text{vol}(U_\varepsilon(Y)) \geq J(\varepsilon)$ , where  $J(\varepsilon)$  denotes the volume of the  $\varepsilon$ -neighborhood of the projective subspace in  $X$  of (real) dimension  $r$ .

**Exercise:** Give a lower bound on  $\text{vol } U_\varepsilon(Y)$  for large  $m = \dim X$  and small codim  $Y$  using the concentration in  $X$  and Milman's argument that we employed in (G') above and earlier in 3½.28.

(f) Large domains  $U$  in algebraic subvarieties  $X \subset \mathbb{C}\mathbb{P}^n$  do not satisfy (uniform) isoperimetric inequalities unless  $\deg X = 1$ . For example, as a smooth quadric  $X$  in  $\mathbb{C}\mathbb{P}^n$  degenerates to a union of two hyperplanes, it can be cut into two equal pieces along a (real) hypersurface  $S$  of arbitrarily small  $(2n - 3)$ -volume. (Yet the  $\varepsilon$ -neighborhood of this  $S$  must have a significant  $(2n - 2)$ -volume in  $X$  in accordance with the concentration property for  $X$  that we just spent 10 pages proving!) However, one expects that  $X$  can be decomposed into  $d$  (or slightly more than that) pieces, where each piece does satisfy an isoperimetric inequality. In fact, one also expects

this to hold for real algebraic varieties  $X$ , where the mere existence of an isoperimetric inequality is unknown for singular  $X$ . Namely, one expects  $\text{vol}_n(U) \leq C_X(\text{vol } \partial U)^\alpha$  for all small domains  $U$  in  $X$  with some  $\alpha = \alpha(\dim X, \deg X)$ . This underlies the difficulty in finding an appropriate lower bound on the spectrum of the Laplace operator on  $X$  (see [Gro]SGSS on the state of affairs), which does not appear in the complex case (see [Li–Tian]).

**On the development and ramifications of the idea of concentration.** Paul Levy discovered the geometric concentration sometime between 1919 and 1951 and explained it in the second edition of his book on geometric functional analysis (see [Levy]). Levy's fascinating results and ideas had remained largely unknown for 20 years until Vitali Milman realized their importance and ubiquity. In particular, he used Levy's theorem for a short new proof of *Dvoretzky's theorem* (see [Milm]71).

This Dvoretzky theorem is every bit as amazing and beautiful as Levy's result. It says that *every  $N$ -dimensional convex body  $X \subset \mathbb{R}^N$  admits an  $\varepsilon$ -round section by a  $k$ -plane  $L$  passing through a given point  $x_0 \in X$* , where “ $\varepsilon$ -round” means that  $X \cap L$  is pinched between two concentric  $k$ -balls in  $L$  of radii  $R$  and  $(1 + \varepsilon)R$ , and where  $\varepsilon \leq \varepsilon(k, N) \rightarrow 0$  for  $N \rightarrow \infty$  and every fixed  $k$ ). Milman extended Levy's result to some nonspherical spaces (e.g., Grassmannian and Stiefel manifolds) and then pushed forward the idea of concentration as a general unifying principle. Ever since, Milman vigorously promoted the *concentration phenomenon*, as he called it, and the idea was reluctantly accepted by the community of functional analysts, but only after they located in the literature an alternative proof of the spherical isoperimetric inequality based on symmetrization (see [Fie–Lin–Mil]).

A couple of years later, Milman persuaded me to read Levy's book, and after deciphering Levy's terminology, I realized that his proof could easily be rendered rigorous using the geometric measure theory of the 1970's and then applied to all Riemannian manifold with a lower bound on the Ricci curvature (see Appendix C<sub>+</sub>). In fact, I still don't know what to do with the original Levy idea of minimizing the volume of  $U_\varepsilon(\Sigma) \subset X^n$  rather than  $\text{vol}_{n-1}(\Sigma)$  among all hypersurfaces  $\Sigma \subset X$  dividing the volume of  $X$  in a given proportion.) And when  $\text{Ricci} \geq c > 0$ , the generalized Levy isoperimetric inequality turned out to yield new concrete concentration results (see [Gro–Mil]TAI), while the case  $\text{Ricci} \geq c$  for  $c < 0$  did not bring similar fruits, although it had deserved some merit in estimating the spectrum of the Laplace operator. But even this is questionable, since one does not need the full nonlinear variational power of Levy's argument to bound  $\lambda_i(X)$  from below. This can also be achieved by elementary geomet-

ric and/or analytic means, where we do not seem to lose much precision, since Levy's inequality is never sharp for closed manifolds with  $\text{Ricci} \leq 0$  anyway (see [Ber–Gal], Appendix C<sub>+</sub>, [Li–Yau]). Also see [Ledoux] for a simple proof of an asymptotically sharp inequality for  $\text{Ricci} > 0$ .)

Nowadays, the concentration phenomenon blends with geometric branches of probability theory, as is best witnessed by [Tal]<sub>CFII</sub> and [Tal]<sub>NLI</sub>.<sup>1</sup> And the stand we take in this book is that the concentration reflects a convergence of spaces (such as  $S^n$  for  $n \rightarrow \infty$ ) to the one point space, which we conceptualize further in 3.45.

## F. Geometric invariants of measures related to concentration

A general scheme of evaluating the geometric size of a measure  $\mu$  on a metric space  $X$  consists in picking up some metric invariant  $\text{Inv}$  expressing the idea of the size of  $a$  and defining  $\text{Inv}(\mu, m - \kappa)$  as the infimum of  $\text{Inv}(X')$  over all metric spaces  $X' \subset X$  with  $\mu(X') \geq m - \kappa$ . (Here,  $m$  alludes to the mass  $\mu(X)$  and then the condition on  $X'$  can be replaced by  $\mu(X \setminus X') \leq \kappa$ , provided  $m = \mu(X) < \infty$ . And if  $\mu(X) = m = \infty$ , one should distinguish these conditions). We have already done it to  $\text{Inv} = \text{diam}$  and also to the minimal covering number of a space by subsets of diameter  $\leq \varepsilon$ . Notice that these  $\text{Inv}(\mu, m - \kappa)$  are monotone under 1-Lipschitz pushforwards of measures. This suggests making the next step by defining

$$\text{ObsInv}_Y(X, -\kappa) = \text{Inv}(X \xrightarrow{\text{Lip}_1} Y, m - \kappa)$$

for  $m = \mu(X)$ , as the supremum of  $\text{Inv}(f_*(\mu), m - \kappa)$  over all 1-Lipschitz maps  $X \rightarrow Y$ . Notice that this observable  $\text{Inv}_Y(X, -\kappa)$  is also monotone for 1-Lipschitz maps  $(X, \mu) \rightarrow (X', \mu')$  if the original metric invariant  $\text{Inv}$  is monotone for surjective 1-Lipschitz maps. In addition to diameter and covering number, this includes the radius  $\text{Rad } X$  and many other first order invariants (see Ch. 3.D<sub>+</sub>) such as the full (vector-valued) covering invariant accounting for the possibility of covering  $X$  by subsets  $X_1, \dots, X_N$  of diameters  $\text{diam } X_i \leq D_i$ . We can also use higher-order invariants, e.g., the Hausdorff measure of a given exponent (dimension)  $d$ .

**3½.30. Separation distance.** Another kind of invariant of  $\mu$  is defined with given numbers  $\kappa_0, \dots, \kappa_N$  as the supremal  $\delta$  such that there exist subsets  $X_i \subset (X, \mu)$ ,  $i = 0, \dots, N$ , with  $\mu(X_i) \geq \kappa_i$  and  $\text{dist}(X_i, X_j) \geq \delta$

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<sup>1</sup>A wealth of new results appear in Sergey Bobkov's 1997 thesis published in Syktyvkar. Also see [Bob], [Bob–Houd], and [Bob–Led].

for  $i \neq j$ , where

$$\text{dist}(X_i, X_j) \stackrel{\text{def}}{=} \inf_{x_i, x_j} \text{dist}(x_i, x_j)$$

for  $x_i \in X_i$  and  $x_j \in X_j$ . This is called the *separation distance* and is denoted

$$\text{Sep}(X; \kappa_0, \dots, \kappa_N) = \text{Sep}(\mu; \kappa_0, \dots, \kappa_N).$$

Clearly, this  $\text{Sep}$  is monotone for 1-Lipschitz maps  $(X, \mu) \rightarrow (X, \mu')$ .

**3.2.31. Observable central radius.** A metric space  $Y$  with a measure  $\nu$  is called *summable* if the distance function  $\delta(y) = \text{dist}(y_0, y)$  is summable, i.e., satisfies  $\int_Y \delta(y) d\nu(y) < \infty$ . If  $Y$  carries an *affine* structure in addition to a metric, such as in the case of a Banach space, then our (summable) measure  $\nu$  on  $Y$  has a well-defined *center of mass*

$$c(\nu) = (\nu(Y))^{-1} \int_Y y d\nu(y).$$

We define  $\text{CRad}(\nu; m - \kappa)$  as the radius  $\rho$  of the minimal closed ball  $B = B(c(\nu), \rho)$  in  $Y$  around  $c(\nu) \in Y$  having mass at least  $m\nu$

$$\nu(B) \geq m - \nu.$$

Then we define the *observable central radius* of a summable mm space  $X$  by minimizing  $\text{CRad}(f_*(\mu), m - \kappa)$  over all 1-Lipschitz maps  $f: X \rightarrow Y$ . It is clear that

$$\text{ObsCRad} \geq \frac{1}{2} \text{ObsDiam}$$

and

$$\text{ObsCRad}_Y(X; -\kappa) \leq \text{ObsDiam}_Y(X; -\kappa) + \frac{\kappa}{m - \kappa} \text{diam}(X),$$

for  $m = \mu(X)$  (compare 3.42(2)). In fact, there is a much better bound on  $\text{ObsCRad}$  if  $\text{ObsDiam}_Y(X; -\kappa)$  grows *slowly* as  $\kappa$  approaches zero. Let  $\kappa(\rho)$  be the inverse function of  $\rho(\kappa) = \text{ObsDiam}_Y(X; -\kappa)$ ; thus  $\kappa(\rho)$  equals the infimal  $t \in [0, m]$ , where  $m = \mu(X)$ , for which  $\text{ObsDiam}_Y(X; -\kappa) \leq \rho$ . This is a monotone decreasing function on  $\mathbb{R}_+ \ni \rho$  which equals  $m$  at  $\rho = 0$  and goes to zero at infinity. The negative of the differential of  $\kappa(\rho)$  gives us a measure, say  $\nu_* = -d\kappa$  on  $\mathbb{R}_+$  of total mass  $m$ . The center of mass of  $\nu_*$  clearly equals

$$c(\nu_*) = m^{-1} \int_0^\infty \kappa(\rho) d\rho \in \mathbb{R}_+$$

(and the center of mass of this measure restricted to  $[r, \infty)$  is

$$c_r(\nu_*) = r + (\kappa(r))^{-1} \int_r^\infty \kappa(\rho) d\rho.$$

Now, we bound  $\text{ObsCRad}_Y(X; -\kappa)$  in terms of  $\rho = \text{ObsDiam}$  and  $c(\nu_*)$  (which is derived from  $\text{ObsDiam}$ ) by arguing as follows. Let  $f: X \rightarrow Y$  be a 1-Lipschitz map and  $\nu = f_*(\mu)$ . We have a subset  $Y_{1/2} \subset Y$  of diameter  $D_{1/2} \leq \rho(m/2)$  which contains at least half of the total mass of  $\nu$ . Every other subset of mass  $\geq m/2$  necessarily intersects  $Y_{1/2}$ , and so the  $R$ -balls in  $Y$  centered at some point  $y_0 \in Y_{1/2}$  satisfy

$$\nu(B(R)) \geq m - \kappa$$

for  $R = \rho(\kappa) + D_{1/2}$  and  $\kappa \leq m/2$ . What remains is to evaluate the distance between  $y_0$  and the center of mass  $c(\nu)$ . To do this, we look at the measure  $\nu'_*$  on  $\mathbb{R}_+$  which equals the pushforward of  $\nu$  under the map  $y \mapsto \text{dist}(y_0, y)$  and observe that

$$\text{dist}(y_0, c(\nu)) \leq c(\nu'_*).$$

On the other hand, the measures  $\nu_*$  and  $\nu'_*$  on  $\mathbb{R}_+$  have equal mass  $m$  and are related by the inequality

$$\nu'_*[0, \rho + D_{1/2}] \geq \nu_*[0, \rho]$$

for all  $\rho \geq \rho_{1/2} = \rho(m/2)$ , and so

$$c(\nu'_*) \geq c(\nu_*) + 2\rho_{1/2}.$$

Therefore,

$$\begin{aligned} \text{ObsCRad}_Y(X; -\kappa) &\leq \text{ObsDiam}_Y(X; -\kappa) + 3\rho_{1/2} + c(\nu_*) \\ &= \text{ObsDiam}_Y(X; -\kappa) + 3\text{ObsDiam}_Y(X; -m/2) \\ &\quad + m^{-1} \int_0^\infty \kappa(\rho) d\rho, \end{aligned}$$

where  $m = \mu(X)$ .

For example, in the case of  $X = S^n$ , we have  $\nu_*(\rho)$  proportional to  $(\cos \rho)^n dt$  on  $[0, \pi/2]$ , which is bounded by  $e^{-n\rho^2/2}$ , and so  $c(\nu_*) \approx 1/\sqrt{n}$ . Thus,  $\text{ObsCRad}_{\mathbb{R}}(S^n)$  has the same order of magnitude as  $\text{ObsDiam}_{\mathbb{R}}(S^n)$  for  $\kappa \geq 1/2$  (with the convention  $m = \mu(S^n) = 1$ ), and so

$$\text{ObsCRad}_{\mathbb{R}}(S^n) = O(\sqrt{\log \kappa^{-1}}/\sqrt{n}),$$

(which improves (o) in 3 $\frac{1}{2}$ .19).

**3 $\frac{1}{2}$ .32. Product inequalities.** If  $(X, \mu)$  equals the cartesian product of  $(X_1, \mu_1)$  and  $(X_2, \mu_2)$  with the (pythagorean) product metric  $\text{dist}_X = \sqrt{\text{dist}_{X_1}^2 + \text{dist}_{X_2}^2}$ , then obviously

$$\text{diam}(\mu, (m_1 - \kappa_1)(m_2 - \kappa_2)) \leq \sqrt{(\text{diam}(\mu_1, m - \kappa_1))^2 + (\text{diam}(\mu_2, m - \kappa_2))^2}.$$

It follows that

$$\text{diam}(X \xrightarrow{\text{Lip}_1} \mathbb{R}^k, (m - \kappa)^k) \leq \sqrt{k} \text{diam}(X \xrightarrow{\text{Lip}_1} \mathbb{R}, m - \kappa).$$

Furthermore, one has this inequality without  $\sqrt{k}$  if one uses the  $L_\infty$ -metric  $\|y - y'\|_{L_\infty}$  in  $\mathbb{R}^k$  corresponding to the norm  $\|y\|_{\ell_\infty} = \sup_i |y_i|$ ,  $i = 1, \dots, k$ .

**Corollary:** *If a sequence of mm spaces  $X^n$  concentrates to a point in the Levy sense, i.e., satisfies  $\text{ObsDiam}_{\mathbb{R}}(X^n) \rightarrow 0$  for each  $\kappa > 0$ , then  $\text{ObsDiam}_{\mathbb{R}^k}(X^n) \rightarrow 0$  for each  $\kappa > 0$  and  $k = 1, 2, \dots$*

(where we abbreviate  $\text{ObsDiam}_{\mathbb{R}}(X) = \text{diam}(X \xrightarrow{\text{Lip}_1} \mathbb{R}, m\kappa)$  as usual).

The observable central radius  $\rho(\kappa)$  of the space  $X = X_1 \times X_2$  above satisfies, for all  $\kappa_1$  and  $\kappa_2$ ,

$$\rho(m_2\kappa_1 + m\kappa_2) \leq \rho_1(\kappa_1) + \rho_2(\kappa_2)$$

for  $\rho_i(\kappa) = \text{ObsRad}_Y(X_i; -\kappa)$ ,  $i = 1, 2, \dots$ . Here,  $m_i = \mu(X_i)$ ,  $i = 1, 2$ , and  $Y$  is an arbitrary Banach space. This is seen for a given 1-Lipschitz map  $f: X \rightarrow Y$  with an intermediate map  $f_2: X_2 \rightarrow Y$  obtained by averaging  $f$  with respect to the variable  $x_1$ ,

$$f_2(x_2) = m_1^{-1} \int_{X_1} f(x_1, x_2) d\mu_1(x_1).$$

This  $f_2$  is  $\mu_1(x)$ -close to  $f$  outside of a subset of measure  $m_2\kappa_1$  in  $X$  (where we think of  $f_2$  as  $f_2(x_1, x_2) = f_2(x_2)$ ). On the other hand,  $f_2$  is  $\rho_2(x)$ -close to its average over  $X_2$ , which equals the average of  $f$  over  $X$  (where the  $\mu$ -average of  $f$  over  $X$  equals the center of mass of  $f_*\mu$  in  $Y$ ).

Notice that this bound on  $\rho(x)$  applies to the *maximal product metric* on  $X$ , also called the  $\ell_1$ -metric

$$\text{dist}_X = \text{dist}_{X_1} + \text{dist}_{X_2}.$$

Also notice that for  $m_2 = 1$ , our bound implies that

$$\rho(\kappa) \leq \rho_1(\kappa/2) + \rho_2(\kappa/2).$$

If  $Y = \mathbb{R}$ , then the argument can be carried over with  $\text{ObsDiam } X$ , where  $f_2(x_2)$  is defined as the *Levy mean* (see 3.19) of  $f(x_1, x_2)$  in the  $x_1$  variable. This  $f_2$  is also 1-Lipschitz, and thus one sees that the observable diameter  $D(\kappa) = \text{ObsDiam}_{\mathbb{R}}(X; -\kappa)$  satisfies

$$D(m_2\kappa_1 + \kappa_2) \leq 2D_1(\kappa_1) + D_2(\kappa_2)$$

for all  $\kappa_2 > 0$  and  $0 < \kappa_1 < \mu(X_1)/2$ .

**Levy radius.** To make this clearer, one can introduce the *Levy radius*,  $\text{LeRad}(X; -\kappa)$  as the infimal  $\rho$ , such that every 1-Lipschitz function  $f(x)$  satisfies

$$\mu\{x \in X : |f(x) - a_0| \geq \rho\} \leq \kappa,$$

where  $a_0$  stands for the Levy mean of  $f$ . Then the inequality for  $D$  above follows from the two obvious inequalities

$$\text{LeRad}(X; -\kappa) \leq \text{ObsDiam}_{\mathbb{R}}(X; -\kappa)$$

for  $\kappa < \mu(X)/2$  and

$$D(m_2\kappa_1 + \kappa_2) \leq 2\text{LeRad}(X_1; -\kappa_1) + D_2(\kappa_2),$$

which holds for all positive  $\kappa_1$  and  $\kappa_2$ .

Also notice that the first inequality can be trivially reversed:

$$\text{ObsDiam}_{\mathbb{R}}(X; -\kappa) \leq 2\text{LeRad}(X; -\kappa)$$

for all  $\kappa > 0$ .

**Exercise:** Define and study the Levy radius for maps of  $X$  into a *tree*.

**3½.33. Concentration and separation.** Every  $\mu$  has

$$\text{diam}(\mu, m - \kappa) \geq \text{Sep}(\mu, \kappa, \kappa),$$

and moreover,

$$\text{diam}(X \xrightarrow{\text{Lip}_1} \mathbb{R}, m - \kappa) \geq \text{Sep}(X, \kappa, \kappa),$$

as is seen with the truncated distance function  $\kappa \mapsto \max(\delta, \text{dist}(\kappa, X_0))$  in  $X$  with  $X_0, X_1 \subset X$  having measures  $\geq \kappa$  and mutual distance  $\delta$ .

Furthermore, every measure  $\nu$  on  $\mathbb{R}$  has

$$\text{diam}(\nu, m - 2\kappa) \leq \text{Sep}(\nu, \kappa, \kappa)$$

and consequently

$$\text{Sep}(X; \kappa, \kappa) \geq \text{diam}(X \xrightarrow{\text{Lip}_1} \mathbb{R}, m - 2\kappa)$$

for all  $X$  and  $\kappa$ . Thus, *Levy's concentration of  $X^n$  (to a point) is equivalent to*

$$\text{Sep}(X^n; \kappa, \kappa) \xrightarrow{n \rightarrow 0} 0$$

for each  $\kappa > 0$ .

### 3 $\frac{1}{2}$ .34. Observable concentration on compact “screens” $Y \prec X$ .

Let  $Y$  be a metric space which can be covered by  $N$  subsets of diameters  $\leq \delta$ . Then every measure  $\nu$  on  $Y$  satisfies

$$\text{diam}(\nu, m - N\kappa) \leq \text{Sep}(\nu, \kappa, \kappa) + 2\delta.$$

It follows that concentration of  $X^n$  to a point implies that (and is obviously implied by)

$$\text{diam}(X^n \xrightarrow{\text{Lip}_1} Y, m - \kappa) \xrightarrow{n \rightarrow \infty} 0$$

for every compact space  $Y$  and every  $\kappa > 0$ . Thus, *every (observable) image of  $(X^n, \mu_n)$  on a given compact “screen”  $Y$  concentrates to a single (luminous) point for large  $n = n(Y)$ .*

Notice that the rate of concentration of  $\mu_* = f_*(\mu_n)$  on  $Y$  to a point depends only on the covering number  $N = N(Y, \delta)$  of  $Y$ , and even better, this rate can be estimated by the covering properties of the measures  $\mu_*$ . Namely, one has uniform concentration if  $(Y, \mu_*)$  runs over a given precompact subset  $\mathcal{Y} \subset \mathcal{X}$ . In particular, *if  $X^n$  concentrate to a point, and if a sequence of spaces  $Y_i \prec X^{n_i}$  for some sequence  $n_i \rightarrow \infty$  converges in the  $\square_\lambda$ -metric for some  $\lambda \geq 0$ , then the limit is necessarily isomorphic to a one point space. The converse is also true and obvious: if the  $X^n$  (with masses  $\mu_n(X^n) \leq \text{const}$ ) do not concentrate, then there exists a sequence of measures  $\nu_i$  on  $[0, 1]$  coming from  $\nu_i$  on  $X^{n_i}$  via 1-Lipschitz maps such that  $\nu_i$  converge to a measure  $\nu$  on  $[0, 1]$  which is not concentrated at a single point.*

### 3 $\frac{1}{2}$ .35. Expansion coefficient and expansion distance.

Denote by  $\text{Exp}(X; \kappa, \rho)$  the infimal  $e \geq 1$  such that

$$\mu(X_0) \geq \kappa \Rightarrow \mu(U_\rho(X_0)) \geq e\kappa$$

for all subsets  $X_0 \subset X$ , where  $U_\rho(X_0)$  denotes the  $\rho$  neighborhood of  $X_0$ . It is clear that  $\text{Exp}$  is monotone for 1-Lipschitz maps  $(X, \mu) \mapsto (X', \mu')$ , i.e.,

$$\text{Exp}(X', \kappa, \rho) \geq \text{Exp}(X, \kappa, \rho),$$

and  $\text{Exp}$  is well-behaved under the scaling of the measure  $\mu$  of  $X$

$$\text{Exp}(c\mu, c\kappa, \rho) = \text{Exp}(\mu, \kappa, \rho).$$

Another pleasant feature of  $\text{Exp}$  is the self-reinforcing property: *if  $\text{Exp}(X, \kappa, \rho) \geq e$  and  $\text{Exp}(X, e\kappa, \rho') \geq e'$ , then  $\text{Exp}(X, \kappa, \rho + \rho') \geq ee'$ ,*

since  $U_{\rho+\rho'}(X_0) \supset U_{\rho'}(U_\rho(X_0))$  (in fact, one has the equality for *path* metric spaces  $X$ ). This can be repeated several times and shows that

$$\text{Exp}(X, \kappa', \rho) \geq e \Rightarrow \text{Exp}(X, \kappa, k\rho) \geq e^k, \quad (*)$$

provided that the first inequality is valid for all  $\kappa' \in [\kappa, k\kappa]$ .

It is sometimes convenient to express  $\delta$  as a function of  $e$ , and we call this the *expansion distance*,  $\text{ExDis}(X, \kappa, e)$ , which is the infimal (distance)  $\rho$  which suffices for the implication

$$\mu(X_0) \geq \kappa \Rightarrow \mu(U_\rho(X_0)) \geq e\kappa$$

to hold. Here one has the obvious bound on the separation distance by  $\text{ExDis}$ ,

$$\text{Sep}(X; \kappa_0, \kappa_1) \leq \text{ExDis}(X; \kappa_0, e_0) + \text{ExDis}(X, \kappa_1, e_1) \quad (+)$$

provided that

$$e_0\kappa_0 + e_1\kappa_1 \geq m = \mu(X).$$

This by itself is not very useful for bounding  $\text{Sep}(X, \kappa_0, \kappa_1)$  when  $e_0, e_1$  are small, and where both  $\kappa_0$  and  $\kappa_1$  are small compared to  $m$ , but one can combine it with  $(*)$  and conclude that the bound

$$\text{ExDis}(X; \kappa, e_0) \leq \rho_0$$

for some  $e_0 > 1, \rho_0 > 0$ , and  $\kappa \in [\kappa_0, m/2]$  implies that

$$\text{Sep}(X, \kappa_0, \kappa_0) \leq \frac{1}{2}(\log_{e_0}(m/\kappa_0))\rho_0. \quad (+\kappa)$$

In particular, if we have  $m = \mu(X) = 1$ , then

$$\rho(X, e_0) \stackrel{\text{def}}{=} \sup_{0 \leq \kappa \leq 1/2} \text{ExDis}(X; \kappa, e_0)$$

for a given  $e_0 > 1$ , say for  $e_0 = 4/3$ , essentially majorizes the separation distances and hence the observable diameter of  $X$ . Namely,

$$\text{Sep}(X, \kappa, \kappa) \leq \frac{1}{2}\rho(X, e_0) \log_{e_0} \kappa^{-1}$$

(where  $\log_{e_0} = \log / \log e_0$ ), and

$$\text{diam}(X \xrightarrow{\text{Lip}_1} \mathbb{R}; 1 - 2\kappa) \leq \frac{1}{2}\rho(X, e_0) \log_{e_0} \kappa^{-1}.$$

It follows that if spaces  $X^n, n = 1, 2, \dots$  with normalized measures satisfy  $\rho(X, e_0) \rightarrow 0$  for some  $e_0 > 1$ , then they concentrate to a point. In fact,

one only needs  $\text{ExDis}(X^n, \kappa, e_0) \rightarrow 0$  for  $\kappa \in [\kappa_n, 1/2]$ , where  $\kappa_n \rightarrow 0$  as  $n \rightarrow \infty$ .

Notice that the expansion inequality  $\text{Exp}(X, \kappa, \rho) \geq e_0$  for  $\kappa \leq m/2$  implies comparable inequalities for all  $\kappa \leq m - \varepsilon$ . Indeed, just look at the complement  $Y_\rho = X \setminus U_\rho(X_0)$  and observe that  $U_\rho(X_0) \setminus X_0 \supset U_\rho(Y_\rho) \setminus Y_\rho$ . If  $\kappa_0 = \mu(X_0) \geq m/2$ , then  $\kappa_1 = \mu(Y_\rho) \leq m/2$ , and so

$$\mu(U_\rho(X_0)) - \kappa_0 \geq (e_0 - 1)\kappa_1,$$

while  $\mu(U_\rho(X_0)) = m - \mu(Y_\rho) = m - \kappa_1$ . Thus,

$$\mu(U_\rho(X)) \geq \frac{\kappa_0 - (e_0 - 1)m}{e_0}, \quad (\diamond)$$

which is a definite improvement over  $\kappa_0$  insofar as  $\kappa_0$  does not approach  $m = \mu(X)$ . In fact,  $(\diamond)$  can be derived from  $(+)$  above combined with the obvious inequality opposite to  $(+)$ ,

$$\text{ExDis}(X, \kappa, e) \leq \text{Sep}(X, \kappa, m - e\kappa). \quad (-)$$

**Exercise:** Bound  $\text{Exp}(X; \kappa, \rho)$  from below in terms of  $\text{ObsDiam}(X)$ .

Notice that many spaces  $X$  with infinite measures have the following expansion property:  $\text{Exp}(X, \kappa, 1) \geq e_0 > 1$  for all  $\kappa > 0$  (or at least for all  $\kappa \geq \kappa_0$ ). This is essentially equivalent to the *linear isoperimetric inequality* (which amounts to *nonamenability* of the isometry group  $\Gamma$  of  $X$  in the case where  $V = X/\Gamma$  is compact).

Typical examples of such  $X$ 's are provided by complete, simply connected manifolds with *negative curvature*  $K \leq -\text{const} < 0$ , or more generally with  $K \leq 0$  and  $\text{Ricci} \geq -\text{const} < 0$ . Also, every infinite simplicial tree built of unit segments, where each vertex has at least 3 adjacent edges obviously has  $\text{Exp} \geq \lambda > 1$ . What is not obvious is the existence of sequences of *finite* graphs  $X^n$ , built of unit edges and having at most  $k_0$  edges at each vertex (say with  $k_0 \geq 3$ ) and  $\text{Exp}(X^n, \kappa, 1) \geq e_0 > 1$ , while the number of vertices in  $X^n$  goes to infinity as  $n \rightarrow \infty$ . Such graphs  $X^n$  have  $\text{ObsDiam}_{\mathbb{R}} X^n = O(1)$  (and  $\text{AvDi}(X^n) \approx \log n$ ). Their construction is indicated in 3 $\frac{1}{2}$ .44.

**3 $\frac{1}{2}$ .36. Spaces  $\mathcal{Lip}_s/\text{const}$  and their diameters.** Given an mm space  $X$ , we denote by  $\mathcal{Lip}_s = \mathcal{Lip}_s(X)$  the space of  $s$ -Lipschitz functions  $f: X \rightarrow \mathbb{R}$ , and we observe that the  $\text{me}_\lambda$ -metrics on  $\mathcal{Lip}_s$  are invariant under the transformations  $f \mapsto f + c$  for all constant (functions)  $c \in \mathbb{R}$ . Then we pass to the quotient  $\mathcal{Lip}_s/\text{const}$ , where the metrics  $\text{me}_\lambda$  descend and are

still denoted by  $\text{me}_\lambda$ . It is well-known (and obvious from the discussion in 3½.A) that the spaces  $\mathcal{Lip}_s/\text{const}$  are compact with respect to  $\text{me}_\lambda$  for all  $s \geq 0$  and  $\lambda > 0$ . Then we define the  $\text{me}_\lambda$ -diameter of  $X$  as the  $\text{me}_\lambda$ -diameter of  $\mathcal{Lip}_s/\text{const}$  for  $s = 1$ .

Notice that  $\mathcal{Lip}_1/\text{const}$  has a distinguished point denoted  $0 \in \mathcal{Lip}_1/\text{const}$  corresponding to constants, and one may speak of the  $\text{me}_\lambda$  radius of  $X$ , i.e., the minimal radius of the  $\text{me}_\lambda$  ball at 0 covering all of  $\mathcal{Lip}_1/\text{const}$ .

Now we present yet another (obvious) characterization of Levy concentration.

$X^n$  concentrates to a point, i.e., we have  $\text{ObsDiam}_{\mathbb{R}}(X^n) \rightarrow 0$  if and only if the corresponding spaces  $(\mathcal{Lip}_1/\text{const}, \text{me}_\lambda)$  Hausdorff-converge to a single point for some (and hence every)  $\lambda > 0$ , that is, if  $\text{diam}_{\text{me}_\lambda}(\mathcal{Lip}_1 X^n/\text{const}) \rightarrow 0$  for  $n \rightarrow \infty$ .

This raises the question of what happens to  $X^n$  if the spaces  $\mathcal{Lip}_1(X^n)$  Hausdorff-converge to some (compact metric) space  $\mathcal{L}$ . This happens, for example, to  $X^n = S^1 \times S^2 \times \dots \times S^n$ , and we shall address this question in 3½.53.

**The Kuratowski embedding of  $X$  into  $\mathcal{Lip}_1/\text{const}$ .** This embedding is defined by  $x_0 \mapsto d_{x_0}(x) = \text{dist}(x_0, x) : X \rightarrow \mathbb{R}$  with the following factorization by constants, which gives us a topological embedding, say  $I : X \rightarrow \mathcal{Lip}_1/\text{const}$ , and the induced metric on  $X$  denoted  $\text{me}_\lambda^*$ . Since  $\mathcal{Lip}_1/\text{const}$  is compact,  $X$  is precompact with respect to  $\text{me}_\lambda^*$ , and we may compactify  $X$  by completing  $\text{me}_\lambda^*$ . Thus, we get the  $\text{me}_\mu^*$ -compactification  $(\overline{X}, \text{me}_\lambda^*)$  of an arbitrary mm space with finite measure. It follows from the above that the Levy concentration of  $X^n$  implies the Hausdorff convergence of  $\overline{X}^n$  to a single point, i.e.,

$$\text{ObsDiam}_{\mathbb{R}}(X^n) \rightarrow 0 \Rightarrow (\text{diam}(\overline{X}^n), \text{me}_1^*) \rightarrow 0.$$

**Question.** What are the minimal (natural) assumptions on  $X^n$  that would imply the reverse implication

$$(\text{diam}(\overline{X}^n), \text{me}_1^*) \rightarrow 0 \Rightarrow \text{ObsDiam}_{\mathbb{R}}(X^n) \rightarrow 0?$$

In other words, when does the concentration of the distance functions  $x \mapsto \text{dist}(x_0, x)$  on  $X$  for all  $x_0 \in X$  imply the concentration of all 1-Lipschitz functions  $f$  on  $X$ ? For many examples, such as round spheres  $S^n$  and other symmetric spaces, the concentration of the distance function is child's play compared to that for all Lipschitz functions  $f$ . But, if we look at more general spaces, say homogeneous, nonsymmetric ones, or manifold  $X^n$  with

Ricci  $X^n \geq n$ , then establishing the concentration for the distance functions becomes a respectable enterprise.

## G. Concentration, spectrum, and the spectral diameter

**3 $\frac{1}{2}$ .37. The space  $\text{Dir}_1$  and the first eigenvalue.** For the time being, let  $X$  stand for a *Riemannian* manifold and take some (not necessarily Riemannian) measure  $\mu$  on  $X$ . We denote by  $\text{Dir}_1 = \text{Dir}_1(X, \mu)$  the space of locally Lipschitz functions  $f: X \rightarrow \mathbb{R}$  satisfying  $\int_X \|\text{grad } f\|^2 d\mu \leq 1$ , where  $\|\text{grad } f(x)\|$  of a non- $C^1$ -smooth function  $f$  refers to the Lipschitz constant or dilatation at  $x$  (denoted by  $\text{dil}_x f$  in 1.1). We factorize this  $\text{Dir}_1$  by the constants (where the Dirichlet functional  $\int \|\text{grad } f\|^2$  vanishes anyway), and we descend the Hilbert norm  $\|f\|_2 = (\int_X f^2 d\mu)^{1/2}$  from  $L_2(X, \mu)$  to  $L_2/\text{const}$  and thus to our  $\text{Dir}_1/\text{const}$ . Now we define the *spectral diameter* of  $(X, \mu)$  as the diameter of  $\text{Dir}_1(X, \mu)/\text{const}$  with respect to the descended  $L_2$ -metric,

$$\text{SpecDiam}(\mu) = \text{SpecDiam}(X, \mu) = \text{diam}(\text{Dir}_1/\text{const}).$$

Notice that we could make this definition with  $C^1$ -smooth functions  $f$ . This would not change  $\text{SpecDiam}$ , since every Lipschitz function can be approximated by smooth ones with the same (local) dilatation at all  $x \in X$ . Also, observe that

$$\text{SpecDiam} = 2/\sqrt{\lambda_1}$$

for the first eigenvalue  $\lambda_1$  of the *Laplace–Beltrami* operator on  $X$ , assuming that  $X$  is compact and that  $\mu$  is the Riemannian measure of  $X$ , where  $\lambda_1$  is defined via the variational principle (see below). In fact, our definition of  $\text{SpecDiam}(X)$  makes sense for all mm spaces  $X$  with the convention

$$\|\text{grad } f(x)\| = \text{dil}_x f,$$

and so we could *define*  $\lambda_1(X)$  as  $4/(\text{SpecDiam})^2$  for all mm spaces  $X$  (compare (C) below).

Notice that  $\text{SpecDiam}$  and  $\lambda_1$  are invariant under the scaling of the measure and that  $\text{SpecDiam}(\ell X, \mu) = \ell \text{SpecDiam}(X, \mu)$ , where  $\ell X$  means  $\text{dist}_X \sim \ell \text{dist}_X$  as usual.

Now we want to compare  $\text{SpecDiam}$  with the above  $\text{me}_1$ -diameter of  $X$ , i.e., the  $\text{me}_1$ -diameter of the space  $\mathcal{Lip}(X)/\text{const}$ . We assume that  $\mu$  is normalized, and then we obviously have  $\int_X \|\text{grad } f\|^2 d\mu \leq 1$ . Thus,

$$\text{Dir}_1/\text{const} \supset \mathcal{Lip}_1/\text{const}.$$

On the other hand, the  $L_2$  metric majorizes the metric  $\text{me}_1$  by the Chebychev inequality, and thus,  $\text{diam}_{\text{me}_1}((\mathcal{Lip}_1 / \text{const})$  can be bounded in terms of  $\text{SpecDiam}$ . Consequently,

$$\text{SpecDiam } X^n \rightarrow 0 \quad \Rightarrow \quad \text{diam}_{\text{me}_1}((\mathcal{Lip}_1 X^n) / \text{const}) \rightarrow 0,$$

or, equivalently,  $\lambda_1(X) \rightarrow \infty \Rightarrow X^n$  collapses to a point, where we assume that  $\mu_n(X^n) = 1$ .

**3½.38. Spectral bound on ObsDiam.** Let us give a specific bound on Exdis and thus on ObsDiam in terms of SpecDiam. Take a subset  $X_0 \subset X$  of measure  $\mu(X_0) \geq \kappa_0 \leq 1/2$  and, following [Che]RBLD and [Che]lbse, consider the (test) function  $f$  interpolating between two constants  $c_0$  on  $X_0$  and  $c_1$  on  $X_1 = X \setminus U_\rho(X_0)$ , for the (open)  $\rho$ -neighborhood  $U_\rho(X_0)$ , by the distance function between  $X_0$  and  $X_1$  as follows:

$$f(x) = \begin{cases} c_0 + \eta \text{dist}(x, X_0) & \text{for } x \in U_\rho(X_0), \\ c_1 & \text{on } X_1 = X \setminus U_\rho(X_0), \end{cases}$$

where we take  $\eta = \rho^{-1}(c_1 - c_0)$ ; so the function  $f$  is continuous and thus  $\eta$ -Lipschitz on  $X$ . The Dirichlet functional of this  $f$  obviously equals  $\eta^2 \kappa'_\rho$ , where  $\kappa'_\rho$  denotes the measure of the closure of the “annulus”  $U_\rho(X_0) \setminus X_0$  (which may be strictly greater than the measure of  $U_\rho \setminus X_0$ ). We take  $c_1$  such that  $\eta^2 \kappa'_\rho = 1$ , i.e.,

$$c_1 = c_0 + \rho / \sqrt{\kappa'_\rho}.$$

The squared  $L_2$ -norm of this  $f$  equals

$$\|f\|_{L_2}^2 = \int_{\kappa} f^2 d\mu = c_0^2 \kappa_0 + c_1^2 \kappa_1$$

for  $\kappa_1$  being the measure of  $X_1$ . Then, assuming  $\mu(U_\rho(X_0)) \leq e_0 \kappa_0$  with  $e_0 \leq 3/2$  (and recalling that  $\mu(X_0) \leq 1/2 = \mu(X)/2$ ), we obtain the following lower bound on the  $L_2$ -norm of  $f$ ,

$$\|f\|_{L_2}^2 \geq c_0^2 \kappa_0 + \frac{1}{2} \left( c_0 + \frac{\sqrt{2}\rho}{\sqrt{\kappa_0}} \right)^2 \kappa_0 \geq \frac{2}{3} \rho^2,$$

independently of  $c_0$ , which shows that  $\text{SpecDiam}(X) \geq \rho$  since  $f$  was chosen in  $\text{Dir}_1(X, \mu)$ . In other words,

$$\text{Exdis}(X, \kappa, e) \leq \frac{1}{2} \text{SpecDiam}(X) \tag{*}$$

for all  $\kappa \in [0, 1/2]$  and  $e \leq 3/2$ . This implies (see  $(+\kappa)$  in 3 $\frac{1}{2}$ .35) that

$$\text{Sep}(X, \kappa, \kappa) \leq \frac{1}{2} \log_{3/2} \kappa^{-1} \text{SpecDiam}(X)$$

and

$$\begin{aligned} \text{ObsDiam}(X, -2\kappa) &= \text{diam}(X \xrightarrow{\text{Lip}_1} \mathbb{R}, 1 - 2\kappa) \\ &\leq \frac{1}{2} \log_{3/2} \kappa^{-1} \text{SpecDiam}(X) \\ &\leq 2 (\log \kappa^{-1}) \text{SpecDiam}(X) \end{aligned} \quad (\star)$$

(see [Gro–Mil]<sub>TAI</sub>, [Milm]<sub>HPL</sub>, and [Mil–Sch] for further information).

**3 $\frac{1}{2}$ .39. Nonlinear and linear spectra of  $X$ .** The general variational definition of the spectrum is as follows. Consider some homogeneous functional  $E$  on the space of Lipschitz functions  $f$  on  $X$ , such as, for example,

$$\int (\text{dil}_x f(x))^2 d\mu_x / \int f^2(x) d\mu_x ,$$

(where we recall that  $\text{dil}_x$  denotes the Lipschitz constant of  $f$  at  $x$ , which amounts to  $\|\text{grad } f(x)\|$  for Riemannian spaces  $X$ ), or more generally,

$$E(f) = \left( \int (\text{dil}_x f(x))^p d\mu_x \right)^{\frac{1}{p}} / \left( \int f^q(x) d\mu_x \right)^{\frac{1}{q}} .$$

This is thought of as a function  $E$  on the projective space  $P^\infty$  of functions on  $X$ . There are then several ways to extract numerical invariants from  $X$ .

- (A) Define  $\lambda_i^+$  as the infimal  $\lambda$  for which there exists an  $i$  dimensional projective subspace  $P^i \subset P^\infty$ , where  $E \leq \lambda$ .
- (B) Let  $\lambda_i^*$  be the infimal  $\lambda$  such that the inclusion homomorphism

$$H_i(E^{-1}[0, \lambda]; \mathbb{Z}_2) \rightarrow H_i(P^\infty; \mathbb{Z}_2)$$

is surjective.

Notice that since each  $P^i \subset P^\infty$  represents a nonzero class in the homology group  $H_i(P^\infty; \mathbb{Z}_2)$ , one has the bound  $\lambda_i \leq \lambda_i^+$  for all  $i = 0, 1, \dots$ . And if the homogeneous functionals in question are quadratic (as are the  $L_2$ -norm and the Dirichlet functional on Riemannian manifolds), then clearly  $\lambda_i = \lambda_i^+$ . In particular,  $\lambda_1 = 4/(\text{SpecDiam})^2$  for (compact) Riemannian manifolds  $X$ , i.e.,

$$\lambda_1 = \inf_f \int_X \|\text{grad } f\|^2 d\mu / \int_X f^2 ,$$

where  $f$  runs over all Lipschitz functions  $f$  orthogonal to constants, i.e., satisfying  $\int_X f = 0$ . Also observe that the spectra  $\{\lambda_i\}$  and  $\{\lambda_i^+\}$  are monotone for the Lipschitz order on mm spaces (see [Gro]DNES for further information and [Hof-Zehn] for a symplectic rendition of the spectral idea).

There are certain (truly) quadratic alternatives to  $\int_X (\text{dil}_x f)^2$  for non-Riemannian  $X$  which correspond to the spectra of *linear* operators. For example, for every (positive symmetric) function  $K$  on  $X \times X$ , e.g., for the indicator function of the  $\varepsilon$ -neighborhood of the diagonal, one can take the  $L_2$ -norm of  $K(x, x')(f(x) - f(x'))$  on  $X \times X$  as a substitute for  $(\int \| \text{grad } f \|^2)^{1/2}$ . (This works pretty well if  $X$  is the vertex set of a graph with unit edges, in which case the  $\lambda_i$  constructed in this way when  $K(x, x')$  is the incidence matrix of the graph, i.e., the indicator function of the 1-neighborhood of the diagonal in  $X \times X$ , give us the usual combinatorial spectrum; see [Lub] and the references therein.) The  $\lambda_i$ 's one gets in this way essentially constitute the spectrum of the integral operator  $\mathcal{K}$  on (functions on)  $X$  given by the kernel  $K$ . More specifically, one can apply it to the operator  $\mathcal{K}_\varphi$  given by the integral kernel  $K_\varphi(x, x') = \varphi(\text{dist}(x, x'))$  for a function  $\varphi(d)$ , thus getting the maps  $\varphi \mapsto \{\lambda_i = \lambda_i(\varphi)\}$  serving as a rather comprehensive spectral invariant of  $X$ . Furthermore, one can take several functions  $\varphi_i$  and look at the spectra of operators appearing as some (noncommutative) polynomial in the variables  $\mathcal{K}_{\varphi_i}$ . Finally, one can study the operators given by the kernels  $K(x, x')(f(x) - f(x'))$  for functions  $f$  on  $X$  in the spirit of Alain Connes (see [Connes]). But all these possibilities and their relation to the concentration remain largely unexplored, except for the case of the usual  $\lambda_i$  corresponding to  $\text{Dir}_1(f)/\|f\|_{L_2}^2$  on Riemannian manifolds (and graphs)  $X$  where  $\text{Dir}_1(f) = \int_X \langle \text{grad } f, \text{grad } f \rangle = \int_X f \Delta f$ , and so the  $\lambda_i$  appear as the ordinary eigenvalues of the Laplace operator  $\Delta$  on  $X$ .

**3½.40. Evaluation of the spectrum for  $S^n$ .** The spectrum of the Laplace operator on a sufficiently homogeneous space  $X$  can be determined by means of harmonic analysis which combines with (★) above to give nontrivial bounds on  $\text{ObsDiam}_{\mathbb{R}} X$ . The simplest example is the unit sphere  $X = S^n$ , where the first eigenvalue consists of the linear functions  $S^n \subset \mathbb{R}^{n+1} \rightarrow \mathbb{R}$  and is spanned by the coordinate projections, say  $\varphi_i: S^n \rightarrow \mathbb{R}$ ,  $i = 0, \dots, n$ , which clearly satisfy

$$\sum_{i=0}^n \varphi_i^2(x) = 1$$

and

$$\sum_{i=0}^n \|\text{grad } \varphi_i(x)\|^2 = n$$

for all  $x \in S^n$ . Thus,

$$\lambda_1 = \int \|\operatorname{grad} \varphi_i\|^2 / \int \varphi^2 = n, \quad (\Delta)$$

and  $(*)$  above implies

$$\operatorname{ObsDiam}(S^n, -2\kappa) = \operatorname{diam}(S^n \xrightarrow{\operatorname{Lip}_1} \mathbb{R}, 1 - 2\kappa) \leq 2(\log \kappa^{-1})/\sqrt{n} \quad (\circ)$$

which, although somewhat weaker than Levy's inequality  $(*)$  in 3.2.19 is sufficient to conclude that  $\operatorname{ObsDiam}(S^n) \approx 1/\sqrt{n}$ .

**3.2.41. Evaluation of the observable radius  $\operatorname{CRad}(S^n \xrightarrow{\operatorname{Lip}} \mathbb{R}^m, 1 - \kappa)$ .** Start with a measure  $\nu$  on  $\mathbb{R}^m$  having its center of mass at the origin, i.e., satisfying  $\int_{\mathbb{R}^m} \varphi d\nu = 0$  for all linear functions  $\varphi: \mathbb{R}^m \rightarrow \mathbb{R}$  and let us bound  $\lambda_1(\nu)$  as follows. Suppose that the complement to the  $\rho$ -ball around the origin, say  $C(\rho) = \mathbb{R}^m \setminus B(\rho)$ , satisfies  $\nu(C(\rho)) \geq \kappa$  and observe that the coordinate (projections)  $\varphi_i: \mathbb{R}^m \rightarrow \mathbb{R}$ ,  $i = 1, \dots, m$  satisfy

$$\sum_{i=1}^m \varphi_i^2(y) \geq \rho^2$$

for  $y \in C(\rho)$ . It follows that

$$\int_{\mathbb{R}^m} \sum_{i=1}^m \varphi_i^2(y) d\nu(y) \geq \kappa \rho^2.$$

So there exists a (linear) 1-Lipschitz function  $\varphi$  on  $\mathbb{R}^m$  with  $\int_{\mathbb{R}^m} \varphi^2(y) d\nu_x \geq \kappa \rho^2/m$ . Namely, one of the  $\varphi_i$ 's will do. Consequently, if there exists a 1-Lipschitz map  $(X, \mu) \rightarrow \mathbb{R}^m$  sending  $\mu$  to  $\nu$ , then  $X$  supports a 1-Lipschitz function  $f$  such that

$$\int_X f d\mu(x) = 0 \quad \text{and} \quad \int_X f^2 d\mu(x) \geq \kappa \rho^2/m.$$

Therefore, if  $\mu(X) = 1$ , then

$$\lambda_1(X, \mu) \leq m/\kappa \rho^2,$$

and if  $\lambda_1(X, \mu) \geq n$ , then

$$\kappa \rho^2 \leq \frac{m}{n}. \quad (*)$$

**Corollary:**

$$\operatorname{ObsCRad}_{\mathbb{R}^m}(S^n; -\kappa) \leq 2 \frac{1}{\sqrt{\kappa}} \frac{\sqrt{m}}{\sqrt{n}}. \quad (**)$$

Thus, every 1-Lipschitz image of  $S^n$  in  $\mathbb{R}^m$  concentrates to a point if  $n/m \rightarrow \infty$ .

**Remarks and open questions:** (a) It is probably not hard to prove a similar result for maps to  $\mathbb{R}^m$  with the  $\ell_p$ -metric for all  $p > 1$ .

(b) It would be nice to improve (\*\*) by plugging in  $-\log \kappa^1$ , or even better  $\sqrt{-\log \kappa^{-1}}$  instead of  $1/\sqrt{\kappa}$ . Some improvement may be possible with the isoperimetric inequality for  $\nu$  as in Levy's normal law (see 3½.23). In fact, one naively expects that the extremal (least concentrated) maps  $S^n \rightarrow \mathbb{R}^m$  are  $O(m)$ -symmetric.

(c) There is a formal similarity between (\*\*) and (+) in 3.42(9). Are the two related?

(d) For which  $R = R(m, n)$  does the scaled sphere  $RS^n = S^n(R)$  Lipschitz dominate  $S^m = S^m(1)$ ? Also, one asks this for balls, i.e., when  $RB^n \succ B^m$ , and, of course, the question stands for all "interesting" mm spaces, such as compact symmetric spaces, product spaces, complex hypersurfaces, etc. And often we just want to know whether  $RX_\varepsilon \succ Y_\varepsilon$ , where  $X_\varepsilon$  and  $Y_\varepsilon$  are  $\varepsilon$ -close in the  $\square_\lambda$ -metric for a given  $X$  and  $Y$ .

**3½.42. Spectra of product spaces.** It is remarkable, although well-known and easy to prove, that  $\lambda_1(X_1 \times X_2) = \min(\lambda_1(X_1), \lambda_1(X_2))$ . In particular,  $\lambda_1(X \times X \times \dots \times X) = \lambda_1(X) \geq \delta > 0$  (where there are  $n$  factors in the product), for all compact connected Riemannian manifolds  $X$ . Thus,

$$\text{ObsDiam } X^n = O(1) \quad (\square)$$

for  $n \rightarrow \infty$ . This carries the same price tag as (o) above, since the characteristic size of the cartesian power  $X^n$  is  $\approx \sqrt{n}$ .

**Remark.** If  $X$  is a compact Riemannian manifold with *boundary*, then our  $\lambda_i$  correspond to the *Neumann* boundary problem for  $\Delta$ .

**Non-Riemannian products.** To better appreciate (□), look at the cartesian power  $\{0, 1\}^n$ , i.e., *the set of the vertices* of the unit cube in  $\mathbb{R}^n$  with the induced *Euclidean* metric. We claim that *the observable diameter here goes to infinity as  $n \rightarrow \infty$* . In fact,

$$\text{ObsDiam}\{\{0, 1\}^n\} \sim n^{1/4}.$$

To see this, we look at the *summation map* from  $\{0, 1\}^n \subset \mathbb{R}^n$  to  $\mathbb{R}$  given by  $\sigma_n(x_1, x_2, \dots, x_n) \mapsto x_1 + x_2 + \dots + x_n$ . This map sends  $\{0, 1\}^n$  to the segment  $[0, n]$ , and by the central limit theorem, the subsegments  $I_n =$

$[0, n/2 - \sqrt{n}]$  and  $I'_n = [n/2 + \sqrt{n}, n]$  receive definite amounts of the (discrete product) measure of  $\{0, 1\}^n$ . That is, the  $\sigma_n$ -pushforwards of this measure satisfy

$$\mu_n(I_n) = \mu_n(I'_n) \geq \varepsilon_0 > 0$$

for  $n \geq 4$  (with, say,  $\varepsilon_0 = 1/20$ ). On the other hand, the maps  $\sigma_n$  on  $\{0, 1\}^n$  (but *not* on the whole cube  $[0, 1]^n$ ) satisfy

$$|\sigma_n(x) - \sigma_n(y)| \leq \|x - y\|_{\mathbb{R}^n}^2.$$

Therefore, the composition of  $\sigma_n$  (on the pullback of  $I_n \cup I'_n$  in  $\{0, 1\}^n$ ) with the map sending  $I_n \rightarrow 0 \in \mathbb{R}$  and  $I'_n \rightarrow n^{1/4} \in \mathbb{R}$  is a 1-Lipschitz map from  $\sigma_n^{-1}(I_n \cup I'_n) \subset \{0, 1\}^n$  to  $\{0, n^{1/4}\} \subset \mathbb{R}$ . This can be 1-Lipschitz extended to all of  $\{0, 1\}^n$  (and even to all of  $\mathbb{R}^n$  if we care) with a definite amount ( $\approx 5\%$ ) of measure sent  $n^{1/4}$ -distance apart. This shows that

$$\text{ObsDiam}(\{0, 1\}^n, 1 - \kappa) \geq \text{const}(\kappa)n^{1/4},$$

and the opposite asymptotic inequality is explained in 3½.62(2).

**3½.43. Congruence spaces.** Take the group  $SL_2\mathbb{R}$  with a left-invariant Riemannian metric and let  $\Gamma_p \subset SL_2\mathbb{Z} \subset SL_2\mathbb{R}$ , for prime  $p$ , consist of the matrices congruent to  $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \pmod{p}$ . It is well-known (and rather obvious) that the quotient spaces  $X^p = SL_2\mathbb{R}/\Gamma_p$  have finite volumes. And a celebrated theorem of Selberg asserts that these Riemannian manifolds  $X^p = SL_2\mathbb{R}/\Gamma_p$  have  $\lambda_1(X^p) \geq \delta > 0$  for all  $p = 2, 3, 5, 7, 11, \dots$ , and so their observable diameters remain bounded for  $p \rightarrow \infty$ . This should be seen in conjunction with the (easy) estimate of the characteristic size or of the averaged diameter of these spaces

$$AvDi(X^p) \approx \log p.$$

Thus, the scaled spaces  $\varepsilon_p X^p$  for  $\varepsilon_p \rightarrow 0$  and  $\varepsilon_p \log p \geq \text{const} > 0$  provide (highly) nontrivial examples of Levy's concentration phenomenon.

The bound  $\lambda_1 \geq \delta > 0$  remains valid for all *congruence spaces*, i.e., for  $X^p = G/\Gamma_p$ , where  $G$  is a semisimple Lie group and  $\Gamma_p$  is a *congruence subgroup* of some arithmetic  $\Gamma \subset G$  (where the arithmeticity of  $\Gamma$  implies  $\text{vol}(G/\Gamma_p) < \infty$ ). One can take, for example,  $\Gamma_p \subset SL_m\mathbb{Z} \subset SL_m\mathbb{R}$  consisting of the matrices  $\equiv 1 \pmod{p}$  and get  $X^p = SL_m\mathbb{R}/\Gamma_p$  for all  $m \geq 2$ . Here, if  $m \geq 3$ , then the bound  $\lambda_1(X^p) \geq \delta > 0$  for  $p \rightarrow 0$  follows from a pure representation theory for  $SL_m\mathbb{R}$ , namely from Kazhdan's *T-property*, which implies, in particular, that  $\lambda_1(SL_m(\mathbb{R})/\Gamma) \geq \delta > 0$  for all discrete

subgroups  $\Gamma$  with finite covolume (see [Alon–Milman], [Alon], [Lub] and the references therein).

**Remarks:** (a) If  $G/\Gamma$  is noncompact (as is  $SL_n\mathbb{R}/SL_n\mathbb{Z}$ , for instance), then one should specify the space of (Lipschitz) functions  $f$  used in the variational definition of  $\lambda_1$  via  $\int \|\operatorname{grad} f\|^2 / \int f^2$ . However, the answer is insensitive to the particular space of functions we use. For example, we can take the (small) space of  $C^\infty$  functions  $f$  with compact support, or the (larger) space of Lipschitz  $L_2$ -functions  $f$  on  $X = G/\Gamma$ , and we get the same variational spectrum, as a trivial argument shows.

(b) It is customary to divide  $G$  by the maximal compact subgroup  $K$  and to study the spectrum on the locally symmetric (orbispace)  $K \backslash G/\Gamma$ , which corresponds to the spectrum of the Laplace operator on the  $K$ -*invariant* functions on  $G/\Gamma$ . For example, if  $G = SL_2\mathbb{R}$ , we come to the spectrum on the Riemann surface  $SO(2) \backslash SL_2\mathbb{R}/\Gamma$  (which has singular points if we allow torsion in  $\Gamma$ ). But dividing by  $K$  does not essentially change the spectrum; nor does it significantly change the observable diameter (this is rather obvious), and so the discussion above descends to the spaces  $K \backslash G/\Gamma_p$ .

**3½.44. Expanders.** This refers to (sequences of finite) graphs  $X$  with the following two properties.

(a) each vertex in  $X$  has at most  $k_0$  adjacent edges, (where one can stick to  $k_0 = 3$ ).

(b)  $\exp(X, \kappa, 1) \geq e_0 > 1$ , for all  $\kappa \leq \frac{1}{2} \operatorname{card} \operatorname{ver}(X)$  (\*)

where we give the path metric to  $X^n$  having all edges of unit length, and we assign unit mass to each vertex of  $X$ , while the edges carry no measure of their own. Thus, the measure  $\kappa$  above  $x$  corresponds to the cardinality of some subset  $V_0$  in the vertex set  $\operatorname{ver}(X)$ . It is convenient to define the *boundary*  $\partial V_0$  as the set of vertices in  $\operatorname{ver}(X) \setminus V_0$  adjacent to  $V_0$ , i.e.,

$$\partial V_0 = \{x \in \operatorname{ver}(X) : \operatorname{dist}(x, V_0) = 1\}.$$

Then (\*) amounts to *the isoperimetric inequality*

$$\operatorname{card}(V_0) \leq (e_0 - 1)^{-1} \operatorname{card} \partial V_0, \quad (*)'$$

for all  $V_0 \subset \operatorname{ver}(X)$  with  $\operatorname{card}(V_0) \leq \frac{1}{2} \operatorname{card} \operatorname{ver}(X)$ .

It is not hard to exhibit infinite expanders, such as regular trees, but it is a great deal harder to produce a sequence  $X^n$  of *finite* graphs with  $\operatorname{card}(\operatorname{ver}(X^n)) \rightarrow \infty$  satisfying the above (\*) and/or (\*)' with fixed  $k_0$  and  $e_0$ , where we repeat that (\*)' should hold for all subsets  $V_0$  with cardinality

less than half of that of  $\text{ver}(X)$ . (We suggest that the reader try to construct such an example on her/his own in order to better appreciate Margulis' construction indicated below. I myself tried something elementary several times, see e.g., 9.2 in [Gro]FRM, unsuccessfully attempting to bypass a Selberg-type theorem in the expander problem.)

**Margulis' idea.** Start with a finite graph  $X_1$  in the space  $X = G/\Gamma$  which generates the fundamental group of  $X$ . (Notice that this  $\pi_1(X)$  equals  $\Gamma$  if  $G$  is a simply connected Lie group.) Then take the pullback  $X_1^p \subset X^p$  of  $X_1$  for the congruence covering map  $X^p \rightarrow X$ . Since the first eigenvalue  $\lambda_1(X^p)$  remains separated from zero, the expanding coefficient of  $X^p$  is  $\geq e > 1$ . This trivially implies a similar property for  $X_1^p$  with a slightly smaller expansion constant  $e_0 > 1$ . In fact, the vertex set of  $X_1^p \subset X^p$  fairly well approximates  $X^p$  as far as the expansion is concerned. Namely, the measure of each ball  $B = B(R)$  in  $X^p$  for  $R \geq R_0$  obviously satisfies

$$c_1\mu(B) \leq \text{card}(B \cap \text{ver}(X_1^p)) \leq c_2\mu(B)$$

for some  $c_1, c_2 > 0$ , provided that  $X = G/\Gamma$  is compact. This allows a lower bound on the expansion coefficient of  $X_1^p$  in terms of that of  $X^p$  in the case where  $X$  is compact, and the general (noncompact) case requires a minor adjustment (left to the reader).

**Remarks:** (a) Instead of bounding  $\exp(X_1^p; \kappa, 1)$  from below in terms of  $\exp(X^p; \kappa, 1)$  minorized by  $\lambda_1(X^p) \geq \delta > 0$ , one could introduce the *combinatorial* first eigenvalue  $\lambda_1(X_1^p)$  via  $\text{Dir}(f)/\|f\|_{L_2}^2$  for functions  $f$  on  $\text{ver}(X_1^p)$ , where

$$\text{Dir}(f) = \sum_{i,j} (f(x_i) - f(x_j))^2,$$

and the sum is taken over all pairs of adjacent vertices  $x_i, x_j$  (i.e., those having  $\text{dist}(x_i, x_j) \leq 1$  in the combinatorial metric on  $X_1^p$ ). Then one could bound  $\lambda_1(X_1^p)$  from below in terms of  $\lambda_1(X^p)$  and finally deduce the lower bound on  $\exp(X_1^p)$  by applying from that on  $\lambda_1(X_1^p)$ . (We suggest that the reader go through these steps in order to slowly get a better feel for  $\lambda_1$ .)

(b) Expanders appear in theoretical computer science. Their existence can be proved by a probabilistic argument as follows. Take a vertex set of the form  $V = V' \sqcup V''$ , where  $V'$  and  $V''$  are sets of equal cardinality  $n$ , and let  $\Pi_i : V' \rightarrow V'', i = 1, \dots, k$  be bijections. We take  $X$  consisting of the edges  $(v', \Pi_i(v'))$  for all  $v' \in V'$  and  $i = 1, \dots, k$ , and then evaluate the number of those  $k$ -tuples of bijections  $(\Pi_1, \dots, \Pi_k)$  for which  $X$  fails to be expansive, i.e., contains a subset  $V_0 \subset V$  of cardinality  $\leq n = \text{card}(V')$ , such that the set of the vertices adjacent to  $V_0$  (including those in  $V_0$ ) has

cardinality  $\leq e_0 \text{card}(V_0)$  for a suitable  $e_0$ , e.g., for  $e_0 = 1.1$ . Here is how the computation goes. The total number of our graphs equals  $(n!)^k$  for  $n = \text{card}(V') = \text{card}(V'')$ , since these are given by  $k$ -tuples of bijections (permutations)  $V \leftrightarrow V''$ . Then we compute (as in [Lub]) the number of *bad*  $k$ -tuples of bijections, such that some subset  $A' \subset V'$  of cardinality  $r \leq n/2$  goes to a subset  $A'' \subset V''$  of cardinality  $\leq s = [3r/2]$  under all  $k$  bijections, where  $[·]$  denotes the integer part of a number. There are  $\left( \binom{s}{r} (n-r)! \right)^k$  bad  $k$ -tuples of bijections for given  $A'$  and  $A''$ , and the number of possible  $A$  is  $\binom{n}{r} \binom{n}{s}$ . So, the totality of the bad choices equals  $\sum_{r=1}^{[n/2]} B(r)$  for  $B(r) = \binom{n}{r} \binom{n}{s} \left( \binom{s}{r} (n-r)! \right)^k$ . To bound this sum, we evaluate the ratios  $B(r+1)/B(r)$  for  $r+1 \leq n/2$ , which we write as  $R_1 R_2 (R_3 R_4)^k$ , where

$$R_1 = \binom{n}{r+1} / \binom{n}{r} = \frac{n-r}{r+1} < n,$$

$$R_2 = \binom{n}{s'} / \binom{n}{s} \leq n^2$$

$$\text{as } s' = \left[ \frac{3(r+1)}{2} \right] \leq \left[ \frac{3r}{2} \right] + 2 = s + 2,$$

$$R_3 = \binom{s'}{r+1} / \binom{s}{r} \leq 10$$

since  $s \leq 3r/2$ , and

$$R_4 = (n-r-1)!/(n-r)! = (n-r)^{-1} \leq 2n^{-1}.$$

Thus,  $B(r+1)/B(r) \leq 1$  for  $k \geq 4$  and  $n \geq 100$ . Consequently,

$$\sum_{r \leq n/2} B(r) \leq n B(1) \leq n^3 (2(n-1)!)^k < (n!)^k$$

for  $k \geq 4$  and  $n \geq 100$ . It follows that not all  $k$ -tuples of bijections are bad, provided that  $k \geq 4$  and  $n \geq 100$ .

Now, if a graph  $X$  corresponds to a good  $k$ -tuple, then every  $V_0 = V'_0 \cup V''_0$  for  $V'_0 = V_0 \cap V'$  and  $V''_0 = V_0 \cap V''$ , clearly has

$$\text{card}(\partial V_0) \geq \text{card}(\partial V'_0) - \text{card}(V''_0).$$

If  $\text{card} V'_0 \geq \text{card} V''_0$ , then this makes  $\text{card} \partial V_0 \geq \text{card}(V_0)/4 - 1$ , which settles the matter. Moreover, if  $\text{card} V''_0 > \text{card} V'_0$ , then we observe that the

computation above shows that the number of bad  $k$ -tuples of bad bijections  $V' \rightarrow V''$  is *much* smaller than  $(n!)^k$ , and so there is a good bijection for which all  $k$  inverse maps  $V'' \rightarrow V'$  are also good. This makes  $\text{card } \partial V_0 \geq \text{card}(V_0)/4 - 1$  in any case.

Isn't it amazing that such a crude computation produces the desired conclusion? And even more amazingly, it does so just barely, leaving us with a pretty big residue  $\approx (n!)^k/n^{k-3}$  of bad graphs out of a total of  $(n!)^k$ . (See [Lub] and [Alon] for information and references.)

## H. Observable distance $H_\lambda$ on the space $\mathcal{X}$ and concentration $X^n \rightarrow X$

**3<sub>2</sub><sup>1</sup>.45. The metrics  $H_\lambda \mathcal{L}_1$  on  $d$  functions and  $H_\lambda \mathcal{L}_1$  on mm-spaces.** We are going to introduce a new metric in the space  $\mathbf{X}$  of isomorphism classes of mm spaces, with respect to which the convergence of spaces  $X^n \subset \mathbf{X}$  to a one point space would correspond to  $\text{ObsDiam}(X^n) \rightarrow 0$ . We follow the same general scheme as in the definition of  $\square_\lambda$  and therefore start by defining a new metric on the space  $D$  of functions  $d: X \times X \rightarrow \mathbb{R}_+$ , where  $X$  is a measure space and  $d$  are positive symmetric functions satisfying the triangle inequality. Each  $d$  on  $X \times X$  defines a distinguished subset of functions on  $X$ , namely those which are 1-Lipschitz with respect to  $d$ , call it  $\mathcal{Lip}(d)$ , and we set

$$H_\lambda \mathcal{L}_1(d, d') = \text{dist}_H(\mathcal{Lip}_1(d), \mathcal{Lip}_1(d')),$$

where the Hausdorff distance  $\text{dist}_H$  between subsets of measurable functions on  $X$  is taken for the metric  $m_\lambda$  in this space of functions  $X \rightarrow \mathbb{R}$ . It is clear that  $H_\lambda \mathcal{L}_1$  is a metric. Indeed, the map  $d \mapsto \mathcal{L}_1(d)$  is injective, since

$$d(x, y) \leq \varepsilon \quad \Leftrightarrow \quad \exists f \in \mathcal{Lip}_1(d) \text{ such that } f(x, y) \leq \varepsilon.$$

It is also clear that the map  $d \mapsto \mathcal{Lip}_1(d)$  is (uniformly) continuous with respect to the metrics  $\square_\lambda$  on  $D$  and  $\text{dist}_H$  (on subsets of functions with the metric  $m_\lambda$ ) for every  $\lambda > 0$  (where we recall that the metrics  $\square_\lambda$  are mutually equivalent for all  $\lambda > 0$ , and that the metrics  $m_\lambda$  are also mutually equivalent for positive  $\lambda$ ). It follows that the identity map

$$(D, \square_\lambda) \longrightarrow (D, H_\lambda \mathcal{L}_1)$$

is (uniformly) continuous. Thus, the two metrics  $\square_\lambda$  and  $H_\lambda \mathcal{L}_1$  are topologically equivalent on each *compact* subset in  $D$ .

We define the distance  $\underline{H}_\lambda \mathcal{L}\iota$  between two mm spaces  $X$  and  $X'$  of mass  $m$  with the use of a measurable parametrization of  $X$  and  $X'$  by the segment  $[0, m]$ , where we minimize the  $H_\lambda \mathcal{L}\iota$  distance in  $D = D([0, m])$  of the pullbacks  $d$  and  $d'$  of the  $\text{dist}_X$  and  $\text{dist}_{X'}$  to  $[0, m]$  over all such parametrizations. One sees easily that this  $\underline{H}_\lambda \mathcal{L}\iota_1$  is indeed a metric, in particular

$$\underline{H}_\lambda \mathcal{L}\iota_1(X, X') = 0 \quad \Rightarrow \quad X \text{ is isomorphic to } X'.$$

In fact,  $\underline{H}_\lambda \mathcal{L}\iota_1$  is topologically equivalent to  $\square_\lambda$  on each *compact* subset in  $\mathcal{X}_m$ , and the implication above follows from the corresponding property of  $\square_\lambda$ . (In fact, one only needs to check this for finite spaces  $X$ , since these are  $\square_\lambda$ -dense in  $\mathbf{X}$ .) Finally, we extend  $\underline{H}_\lambda \mathcal{L}\iota_1$  to spaces of different masses  $m$  and  $m'$  as in Ch. 3½.B+.

Now we recall that the observable diameter of  $X$  carries essentially the same message as the  $\text{me}_\lambda$ -diameter of the space  $\mathcal{Lip}_1(X)$  for some  $\lambda > 0$ , e.g.,  $\lambda = 1$ , and thus  $\text{ObsDiam}_{\mathbb{R}} X^n \xrightarrow[n \rightarrow \infty]{} 0$  is equivalent to  $\underline{H}_1 \mathcal{L}\iota_1$ -convergence of the sequence  $X^n$  to a one point space (where we could equally use  $\underline{H}_\lambda \mathcal{L}\iota_1$  for a given  $\lambda > 0$ ).

**3½.46. Concentration  $X^n \rightarrow X$ .** The word “concentration” refers to  $\underline{H}_1 \mathcal{L}\iota_1$ -convergence, and we want to get a geometric picture of this, where  $X$  consists of more than one point (which is similar to what happens to the Hausdorff collapse in 3.35).

**Example:** Set  $X^n = Y \times Z^n$  with  $\text{ObsDiam } Z^n \rightarrow 0$ . Let us show that indeed

$$\text{ObsDiam } Z^n \rightarrow 0 \quad \Rightarrow \quad X^n \xrightarrow{\underline{H}_1 \mathcal{L}\iota_1} Y,$$

where we assume, to avoid notational complications, that  $\mu(Z^n) = 1$  and that neither  $X$  nor  $Z^n$  have atoms. We denote by  $p_n : X^n \rightarrow Y$  the projection and measurably identify  $X^n$  with  $[0, m]$  for  $m = \mu(X)$ . Then our parametrizations of  $X^n$  and  $Y$  coincide with the identity map  $X^n \rightarrow X^n$  and with the projection  $p_n : X^n \rightarrow Y$  correspondingly. Let us evaluate the Hausdorff distance between the subspace

$$\mathcal{Lip}_1(X^n) = \{\text{functions on } X^n \text{ with the } \text{me}_1\text{-metric}\}$$

and the pullback  $p^*(\mathcal{Lip}_1(Y))$ . Since  $p$  is 1-Lipschitz,

$$p^*(\mathcal{Lip}_1(Y)) \subset \mathcal{Lip}_1(X^n),$$

and all we have to show is that

$$\mathcal{Lip}_1(X^n) \subset U_\varepsilon(p^*(\mathcal{Lip}_1(Y))),$$

where  $U_\varepsilon$  stands for the  $\varepsilon$ -neighborhood and where  $\varepsilon$  should be small for small  $\text{ObsDiam}(Z^n)$ . We observe that  $p^*(\mathcal{Lip}(Y))$  consists of exactly those 1-Lipschitz functions on  $X^n$  which are constant on the fibers of the map  $p_n$ , i.e., on each  $x \times Z^n \subset X^n = Y \times Z^n$ , and we project  $\mathcal{Lip}_1(X^n)$  to  $p^*(\mathcal{Lip}_1(Y))$  by taking the Levy mean  $\bar{f}(x)$  of each 1 Lipschitz function  $f(x) = f(y, z)$  in the  $z$ -variable. The  $\text{me}_1$ -displacement for this projection is controlled by the Levy radius of  $Z^n$  as in  $3\frac{1}{2}.32 - 3\frac{1}{2}.36$

$$\text{LeRad}(Z^n; -\kappa) \leq -\rho \quad \Rightarrow \quad \text{me}_1(f, \bar{f}) \leq \max(\kappa, \rho).$$

This yields a concentration  $X^n \rightarrow Y$  under our assumption that  $\text{ObsDiam}_{\mathbb{R}}(Z^n) \rightarrow 0$ , since it is equivalent to  $\text{LeRad}(Z^n) \rightarrow 0$ .

Let us isolate the relevant properties of the projections  $p_n$ . We want to comprehend how the general measurable maps  $p_n: X^n \rightarrow Y$  which, so to speak, *enforce* concentration of  $X^n$  to  $Y$ , meaning

$$\text{dist}_H(\mathcal{Lip}_1(X^n), p_n^*(\mathcal{Lip}_1(Y))) \xrightarrow{n \rightarrow \infty} 0,$$

where clearly a so enforced concentration implies the ordinary one, i.e., the  $\underline{H}_\lambda \mathcal{L}\ell_1$ -convergence of  $X^n$  to  $Y$ , provided that the maps  $p_n: X^n \rightarrow Y$  are measure-preserving. In what follows, we abbreviate  $\mathcal{L} = \mathcal{Lip}_1(X)$ ,  $\mathcal{L}_n = \mathcal{L}(X^n)$ , and  $\mathcal{L}^* = p^*(\mathcal{Lip}_1(Y)) \subset \mathcal{L}$  for a given map  $p: X \rightarrow Y$ . And if we deal with a sequence  $p_n: X^n \rightarrow Y$ , we write  $\mathcal{L}_n^*$  for  $p_n^*(\mathcal{Lip}_1(Y)) \subset \mathcal{L}_n$ . Our objective is to bound the Hausdorff distance between  $\mathcal{L}$  and  $\mathcal{L}^*$  in the space of measurable functions on  $X$  with the  $\text{me}_1$  metric. Thus, we want to bound  $\varepsilon$  for which

$$\text{I. } \mathcal{L}^* \subset U_\varepsilon(\mathcal{L})$$

$$\text{II. } \mathcal{L} \subset U_\varepsilon(\mathcal{L}^*),$$

where  $U_\varepsilon$  denotes the  $\varepsilon$ -neighborhood in the  $\text{me}_1$  metric.

**(A) Giving a name to the inclusion  $\mathcal{L}^* \subset U_\varepsilon(\mathcal{L})$ .** First we notice that

$$\mathcal{L}^* \subset \mathcal{L} \quad \Leftrightarrow \quad \text{the map } p: X \rightarrow Y \text{ is 1-Lipschitz.}$$

We then *define* a map  $p$  to be *1-Lipschitz up to (an additive error)  $\varepsilon$*  if  $\mathcal{L}^* \subset U_\varepsilon(\mathcal{L})$ . If we spell this out for a sequence of maps  $p_n: X^n \rightarrow Y$ , then we come to the following

**I<sub>A</sub> Almost tautology.** *One has  $\mathcal{L}^* \subset U_{\varepsilon_n}(\mathcal{L})$  with  $\varepsilon_n \rightarrow 0$  for  $n \rightarrow \infty$  if and only if the inequality*

$$\text{dist}(p(x), p(x')) \leq \text{dist}(x, x') + \delta_n \tag{*}$$

holds for all  $x$  and  $x'$  in subsets  $V_n \subset X^n$ , where  $\delta_n \rightarrow 0$  and  $\mu(X^n \setminus V_n) \rightarrow 0$  for  $n \rightarrow \infty$ .

(This agrees with our earlier definition of “1-Lipschitz up to  $\varepsilon$ .“)

**(B) Concentration and parallelism between the fibers.** The inclusion  $\mathcal{L} \subset U_\varepsilon(\mathcal{L}^*)$  says that every 1-Lipschitz function  $f$  on  $X$  admits an  $\varepsilon$ -small perturbation  $f'$  (where “ $\varepsilon$ -small” refers to the metric  $me_1$ ) such that

**II<sub>B</sub>.** The function  $f'$  is constant on the fibers of  $p: X \rightarrow Y$ , i.e., it equals  $g \circ p$  for some function  $g$  on  $Y$ .

**III<sub>B</sub>.** Moreover, one can choose this  $f'$  in such a way that  $g$  is 1-Lipschitz on  $Y$ .

These II<sub>B</sub> and III<sub>B</sub> require somewhat different properties of  $p$ . The first of the two implies, as we shall see presently, that (most of) the fibers  $X_y = p^{-1}(y) \subset X$ ,  $y \in Y$ , are roughly  $\varepsilon$ -concentrated, i.e., have observable diameters  $O(\varepsilon)$ . In fact, we shall state and prove this not for the fibers themselves, but for the  $\delta$ -fibers  $X_B = p^{-1}(B) \subset X$ , with  $\delta$ -small underlying open subsets  $B \subset Y$ . The advantage of this is a guaranteed positive measure  $\mu_X(X_B) > 0$ , which facilitates our discussion.

On the other hand, condition III<sub>B</sub> makes these (concentrated) fibers  $X_y$  and  $X_{y'}$  mutually “almost parallel” with distance  $\text{dist}(y, y') + O(\varepsilon)$  between them. In fact, due to the concentration of the fiber  $X_y$ , the distance  $\text{dist}(x, y')$  is close to a constant on most of  $X_y$ , and we claim that this constant is close to  $\text{dist}(y, y')$ . Here again, it is more convenient to state and prove everything for the  $\delta$ -fibers.

We conclude this discussion by noting that the  $\varepsilon$ -perturbation  $f \sim f'$  which makes  $f$  constant on the fibers can be achieved by taking the means (averages) of  $f$  along the fibers. Actually, we prefer Levy’s mean rather than the average in order to block the possible summability problem. Besides, we shall use the  $\delta$  fibers with  $\delta > 0$  to have enough elbow room with the measure  $> 0$ .

**(C) Relative concentration of  $X_n$  over  $Y$ .** We say that a sequence of maps  $p_n: X^n \rightarrow Y$  effectuates relative concentration of  $X^n$  over  $Y$  as  $n \rightarrow \infty$  if

$$\limsup_{n \rightarrow \infty} \text{ObsDiam}(X_B^n, -\kappa) \leq \text{diam } B$$

for every bounded open subset  $B \subset Y$  and each  $\kappa > 0$ , where  $X_B^n = p_n^{-1}(U)$ .

**Observation:** If measure-preserving maps  $p_n$  enforce concentration of  $X^n$  to  $Y$ , then they also effectuate relative concentration of  $X^n$  over  $Y$ .

**Proof.** We must show that every 1-Lipschitz function  $f = f_n$  on  $X_B^n$  has oscillation  $\leq \delta + \varepsilon_n$  for  $\delta = \text{diam } B$  and  $\varepsilon_n \rightarrow 0$  outside a subset of measure  $\kappa$  in  $X_B^n$ . To show this, we extend  $f$  to a 1-Lipschitz function  $\tilde{f}$  on all of  $X^n$ , where it is  $\varepsilon_n$ -close to  $\tilde{f}' = g_n \circ p_n$  for  $g_n$  being 1-Lipschitz on  $Y$  and with the  $\varepsilon_n$ -closeness referring to the  $m_1$ -metric. Clearly, the restriction  $f'_n = \tilde{f}'|_{X_B}$  has oscillation at most  $\delta + o(n)$  away from a subset of measure  $o(1)$ , since the maps  $f_n$  are 1-Lipschitz with additive errors  $o(1)$  (where  $o(1)$  means “going to zero as  $n \rightarrow \infty$ ”). On the other hand,  $f'_n$  is  $\varepsilon_n$ -close to  $f$  on  $X_B^n$  for  $\varepsilon_n \rightarrow 0$ , and the proof follows.

**(D) Closeness and parallelisms between the fibers.** Let us define the following  $\kappa$ -distance between two measurable subsets  $A_1$  and  $A_2$  in an mm space  $X$

$$\text{dist}_+(A_1, A_2; +\kappa) = \sup \text{dist}(A'_1, A'_2),$$

where  $A'_1 \subset A_1$  and  $A'_2 \subset A_2$  run over the pairs of subsets such that

$$\mu(A'_1) \geq \kappa \quad \text{and} \quad \mu(A'_2) \geq \kappa,$$

and where we recall that

$$\text{dist}(A'_1, A'_2) = \inf_{\substack{a'_1 \in A'_1 \\ a'_2 \in A'_2}} \text{dist}(a'_1, a'_2).$$

**Observation:** Let  $p_n : X^n \rightarrow Y$  be a measure preserving map as before which enforces concentration of  $X^n$  to  $Y$ , take  $\kappa > 0$  and consider subsets  $A_1 = A_1(n)$  and  $A_2 = A_2(n)$  in  $X^n$  of measures  $\geq \kappa$ . Denote by  $B_1$  and  $B_2$  their  $p_n$ -images in  $Y$  and let

$$\delta = \max(\text{diam } B_1, \text{diam } B_2).$$

Then

$$\text{dist}_+(A_1, A_2; +\kappa) \leq \text{dist}(B_1, B_2) + 2\delta + \varepsilon_n,$$

where  $\varepsilon_n \rightarrow 0$  as  $n \rightarrow \infty$ . (In fact,  $\varepsilon_n = \varepsilon_n(\kappa)$  admits a bound in terms of  $\text{dist}_H(\mathcal{L}_n, \mathcal{L}_n^*)$  essentially independently of the particular subsets we choose.)

**Proof.** Suppose we have subsets  $A'_i \subset A_i$ ,  $i = 1, 2, \dots$ , of measure  $\geq \kappa > 0$  and with

$$\text{dist}(A'_1, A'_2) \geq \Delta = \text{dist}(B_1, B_2) + 2\delta + \alpha$$

for some  $\alpha > 0$  independent of  $n$ . Then there is a 1-Lipschitz function  $f$  on  $X$  which equals zero on  $A'_1$  and  $\Delta$  on  $A'_2$ . But this  $f$  cannot be contained in

the  $\varepsilon$ -neighborhood  $U_\varepsilon(\mathcal{L}_n^*)$  if  $\varepsilon$  is sufficiently small and  $\mathcal{L}_n^* \subset U_\varepsilon(\mathcal{L}_n)$  (i.e.,  $p$  is 1-Lipschitz up to  $\varepsilon$ ), since every function  $g$  on  $Y$  such that  $g|_{B_1''} = 0$  for some  $B_1'' \subset B_1$  and  $g|_{B_2''} = \Delta$  for some  $B_2'' \subset B_2$  has Lipschitz constant at least

$$\Delta / (\text{dist}(B_1, B_2) + 2\delta) \geq 1 + \alpha/\Delta,$$

provided that  $B_1''$  and  $B_2''$  are nonempty.

**Concentration remark.** If  $\delta$  is small and  $A_i = p_n^1(B_i)$ ,  $i = 1, 2$ , then these  $A_i$  are almost  $\delta$ -concentrated for large  $n$ , and so the  $\kappa$  distance well-approximates the *actual distance* between the  $\delta$ -fibers  $A_i$  which is given by either of the two functions  $x_1 \mapsto \text{dist}(x_1, A_2)$  for  $x_1 \in A_1$  and  $x_2 \mapsto \text{dist}(x_2, A_2)$  for  $x_2 \in A_2$ . Namely, if  $\kappa \in [\kappa_0, \underline{\kappa}]$  for a fixed  $\kappa_0 > 0$  and  $\underline{\kappa} \leq \frac{1}{2} \min(\mu(B_1), \mu(B_2))$ , then these functions are close (with respect to the  $m_{\text{e}_1}$ -metric) to constants and the observation above implies that the constants are within the range  $\text{dist}(B_1, B_2) \pm \delta$ . So, we can say that the  $\delta$ -fibers of the maps  $p_n: X^n \rightarrow Y$  are *essentially parallel* for  $n \rightarrow \infty$ .

**Example:** If  $p: X \rightarrow Y$  is a Riemannian submersion, e.g.,  $S^{2n+1} \rightarrow \mathbb{CP}^n$ , or the projection  $X = Y \times Z \rightarrow Y$ , then the fibers are honestly parallel, i.e., the function  $\text{dist}(x, X_{y_0})$  is constant on each fiber  $X_y = p^{-1}(y) \in X$ .

**Characteristic distances between the fibers.** If  $A_1$  and  $A_2$  are two sufficiently concentrated fibers of  $p: X \rightarrow Y$  (or  $\delta$ -fibers with a small  $\delta$ ), then the distance function  $\text{dist}(x_1, x_2)$  for  $(x_1, x_2) \in A_1 \times A_2$  is close to its Levy mean (or the ordinary mean, i.e., the average, where this  $\text{dist}(x_1, x_2)$  must be summable) and this mean, call it  $\text{Ledi}(A_1, A_2)$ , is a certain function on  $Y \times Y$

$$\text{Ledi}(y_1, y_2) = \text{Ledi}(X_{y_1}, X_{y_2}),$$

(where one can replace the points  $y_i$  by small  $\delta$ -balls  $B(y_i, \delta)$  if one is bothered by the issue of how to properly define a *nonzero* measure in the fibers). This Ledi is usually significantly greater than the ordinary distance  $\text{dist}(y_1, y_2)$ . For example,  $\text{Ledi}(y, y)$  equals the characteristic size (or the average diameter) of the fiber  $X_y$ , which may be far from zero. To get a clear perspective, one should look again at  $X = Y \times Z$  with a concentrated fiber, e.g.,  $Z = S^n$  with large  $n$ , where

$$\text{Ledi}(y_1, y_2) \approx \sqrt{\text{dist}^2(y_1, y_2) + \pi^2/4},$$

if we use the  $\ell_2$ -product metric in  $Y \times Z$ . More generally, one can modify this picture with a *warping factor*, i.e., a function  $w = w(y)$  which scales the fiber  $X_y = y \times Z$  by  $w(y)$ , replacing it by  $y \times w(y)Z$ . In this case, the function  $\text{Ledi}(y_1, y_2)$  behaves in a somewhat more complicated way.

**Exercise:** Evaluate Ledi( $y_1, y_2$ ) for  $X = [0, 1] \times wS^n$  for a given function  $w(y)$ ,  $y \in [0, 1]$ , e.g., for  $w(y) = e^{ay}$  with large  $a$ .

**3 $\frac{1}{2}$ .47. A criterion for enforced concentration.** We are now about to state and prove an inverse to the tautology and observations above for a given sequence of measure preserving maps  $p_n: X^n \rightarrow Y$ .

**Proposition:** Let  $p_n$  satisfy the following three conditions:

- I. The  $p_n$ 's are 1-Lipschitz up to (additive errors)  $\varepsilon_n \rightarrow 0$  for  $n \rightarrow \infty$ .
- II. The  $\delta$ -fibers are highly concentrated for small  $\delta > 0$  and large  $n = n(\delta)$ .  
Namely, for every  $\varepsilon > 0$ , there exists  $\delta > 0$  such that

$$\text{ObsDiam}(X_B^n, -\kappa) \leq \varepsilon$$

for every  $\delta$ -ball  $B \subset Y$ , every  $\kappa > 0$ , and all sufficiently large  $n \geq n(\varepsilon, \delta, \kappa)$ .

- III. the  $\kappa$ -distance between the  $\delta$ -fibers approaches the distance between the underlying balls for suitable values of  $\delta$  and  $\kappa$ . This means that for every two points  $y_1$  and  $y_2$  in  $Y$  and each  $\varepsilon > 0$ , there exist  $\delta > 0$  such that the  $\kappa$ -distance between  $A_1 = p_n^{-1}(B(y_1, \delta))$  and  $A_2 = p_n^{-1}(B(y_2, \delta))$  satisfies

$$\text{dist}_+(A_1, A_2; +\underline{\kappa}) \leq \text{dist}(y_1, y_2) + \varepsilon',$$

(where the opposite inequality  $\text{dist}_+(A_1, A_2; +\underline{\kappa}) \geq \text{dist}(y_1, y_2) - \varepsilon'$  follows from I) for  $\underline{\kappa} = \frac{1}{2} \min(\mu B(y_1, \delta), \mu B(y_2, \delta))$  (with  $B(y, \delta)$  denoting the gd-ball in  $Y$  around  $y \in Y$ ) and all  $n \geq n(\varepsilon', \delta, \underline{\kappa})$ .

Then the  $p_n$  enforce the concentration of  $X^n$  to  $Y$ .

**Idea of the proof.** Our task is to slightly perturb a 1-Lipschitz function  $f$  on  $X^n$  to  $f' = g \circ p_n$ , where  $g$  is 1-Lipschitz on  $Y$ . And it is sufficient to have  $g$  only 1-Lipschitz up to an additive error  $o(1)$  for  $n \rightarrow \infty$ , since this can be further perturbed to the desired honestly 1-Lipschitz function. Now, we make up such  $g$  by Levy-averaging  $f$  along the  $\delta$ -fibers of  $p_n$ . Namely, we cover most of  $Y$  by small  $\delta$ -balls  $B_i = B_{i,n}$ ,  $i = 1, \dots, N$ , where  $\delta \leq \delta_n \rightarrow 0$  for  $n \rightarrow \infty$  and  $N = N(n) \rightarrow \infty$ , while

$$\mu(X^n \setminus \bigcup_{i=1}^N B_i) \leq \kappa_n \xrightarrow{n \rightarrow \infty} 0$$

for the measure  $\mu = \mu_n$  on  $X^n$ . To make everything work right, we must assume that  $\delta_n$  and  $\kappa_n$  decay very slowly with  $n \rightarrow \infty$  and  $N(n)$  grows

very slowly. Actually, we choose our balls for some  $n$  and then we allow  $n$  to grow for a long time before we switch to a new set of balls  $B_i$ . Then we again let the balls stay still for a long time as  $X^n$  concentrates more and more to  $Y$  as  $n$  increases. In other words,  $\text{dist}_H(\mathcal{L}_n, \mathcal{L}_n^*)$  must be kept relatively small, i.e., less than some  $\varepsilon_n = \varepsilon_n\{B_i\}$ , where, in particular, this  $\varepsilon_n$  is much smaller than  $\delta_n, \kappa_n$  and  $N^{-1}(n)$ . It follows from **II** that the  $\delta$ -fibers  $A_i = p_n^{-1}(B_i)$  are highly concentrated, and so the Levy means  $g_i$  of  $f|_{A_i}$  are close to  $f|_{A_i}$ . Then **III** and the König matching theorem (see Ch. 3½.C) imply that

$$|g_i - g_j| \leq \text{dist}(B_i, B_j) + o(1)$$

as  $n \rightarrow \infty$ . Indeed, the concentration of  $A_j$  implies high concentration of the distance function  $a_j \mapsto \text{dist}(a_j, A'_i)$  on  $A_j$  for every subset  $A'_i \subset A_i$ . Then **III** shows that the  $\rho$ -neighborhood in  $X$  of a subset  $A'_i \subset A_i$  with  $\mu(A'_i) \geq x' > 0$  will contain almost full measure of  $A_j$ , provided that

$$\rho \geq \text{dist}(B_i, B_j) + 4\delta + \varepsilon' + \varepsilon = \text{dist}(B_i, B_j) + o(1)$$

for all sufficiently large  $n \geq n(\delta, \varepsilon, \varepsilon', x') \rightarrow \infty$ . The same equality applies to subsets  $A'_j \subset A_j$  and leads to a bound on the  $\text{di}_\lambda$ -distance between the normalized measures  $\mu_i = \mu^{-1}(A_i)\mu|_{A_i}$  and  $\mu_j = \mu^{-1}(A_j)\mu|_{A_j}$ . Consequently, we can bound the transportation metric via the König theorem. In fact, what we get and what we truly need is that the  $\rho_{ij}$ -neighborhood in  $X$  of a subset  $A'_i \subset A_i$  with  $\mu(A'_i) \geq \kappa' > 0$  will contain almost full measure of  $A_j$  provided that

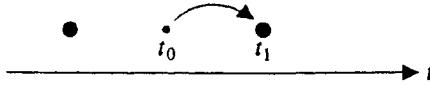
$$\begin{aligned} \rho_{ij} &\geq \text{dist}(B_i, B_j) + 4\delta + \varepsilon' + \varepsilon \\ &= \text{dist}(B_i, B_j) + o(1) \end{aligned}$$

for all sufficiently large  $n \geq n(\delta, \varepsilon, \varepsilon', \kappa') \rightarrow \infty$ . Then our bound on  $|g_i - g_j|$  follows via the following, obvious

**(5') Lemma:** *Let  $\mu_1$  and  $\mu_2$  be two probability measures on a metric space  $X$ , such that  $\text{ObsDiam}(\mu_i, -1/4) \leq \Delta$ ,  $i = 1, 2$ , and  $\mu_1$  admits a  $\rho$ -transportation to  $\mu_2$  of deficiency  $\kappa \leq 1/4$ . Then the Levy means of each 1-Lipschitz function  $f$  on  $X$  with respect to  $\mu_1$  and  $\mu_2$ , call them  $g_1$  and  $g_2$ , satisfy*

$$|g_1 - g_2| \leq \rho + 2\Delta.$$

**Warning:** The Levy mean of  $f$  with respect to a measure  $\mu$  is not uniformly continuous in  $\mu$  as is seen by moving a small central atom away from the center.



Here, the transportation of this tiny mass moves the Levy mean of the coordinate  $t$  from  $t_0$  to  $t_1$ .

Now, the bound  $|g_i - g_j| \leq \text{dist}(B_i, B_j) + o(1)$  shows that the function  $g(y)$  assigning to each  $y \in \bigcup_{i=1}^N B_i$  the value  $g_i$  for some  $B_i \ni y$  is 1-Lipschitz up to an additive error  $o(1)$ , and the proof follows. We suggest that the reader fill in the details by setting in order the qualifiers and chasing all the  $\varepsilon$ 's and  $\delta$ 's. (This will go smoothly unless we missed something in our **II** and/or **III**.)

**3½.48. On relativization of concentration invariants.** The above discussion suggests a definition of a  $\delta$ -invariant attached to a Borel map  $f: X \rightarrow Y$  and some geometric invariant  $\text{Inv}$  as follows.

$$\delta\text{-Inv}(X/Y) = \sup_{X'} \text{Inv}(X')$$

for  $X'$  running over all  $\delta$ -fibers of  $X$ .

**Example:** If  $X = Y \times Z$ , then the  $\delta$ -observable diameter of  $X$  over  $Y$  is roughly bounded by  $\delta + \text{ObsDiam}(Z)$ . In fact, this is literally true for the central  $\delta$ -radii,

$$\delta\text{-ObsCRad}_B(X/Y; -\kappa) \leq \delta + \text{ObsCRad}_B(Z; -\kappa)$$

for every Banach space  $B$  (e.g.,  $B = \mathbb{R}$ ), and

$$\delta\text{-LeRad}(X/Y; -\kappa) \leq \delta + \text{LeRad}(Z; -\kappa).$$

This follows from the discussion above.

**(6') Concentration modulo a partition.** There is another relativization of our concentration invariants which applies to an arbitrary measurable partition  $\Pi$  of  $X$  into subsets  $X_y$  for  $y \in Y = X/\Pi$ , where we stay blind to the geometry of  $Y$ . Recall that there exist canonical probability measures in almost all fibers  $X_y$  (where  $Y$  carries the quotient measure), and so one can average every  $L_1$ -function  $f$  along the fibers. Then one defines  $\text{ObsCRad}_{\mathbb{R}}(X/\Pi; -\kappa)$  as the infimal  $\rho$  such that each 1-Lipschitz function  $f(x)$  is  $\rho$ -close to its fiberwise average  $\bar{f}_{\Pi}(x)$  outside a subset of measure  $\kappa$ ,

$$\mu\{x \in X : |f(x) - \bar{f}_{\Pi}(x)| \leq \rho\} \leq \kappa.$$

One can also use the fiberwise Levy mean  $\check{f}_{\Pi}(x)$  of  $f(x)$  and thus define  $\text{LeRad}(X/\Pi; -\kappa)$ , which has the advantage of not requiring  $f$  to be  $L_1$ .

One can go further and look for the infimal  $\rho = \rho(x)$  such that for each 1-Lipschitz function  $f$ , there exists a function  $f'$  on  $X$  which is constant on each fiber and satisfies

$$\mu\{x \in X : |f(x) - f'(x)| \leq \rho\} \leq \kappa,$$

which relativizes (a slightly modified) ObsDiam. Here, there is an extra modification achieved by restricting to 1-Lipschitz functions  $f'$  constant on the fibers. We suggest that the reader study the relations among all these relative radii, generalizing what was done in the absolute case in which  $Y$  consisted of a single point. We also suggest looking in a similar vein at the space  $\text{Lip}_1(X)/\text{const}_\Pi$ , where  $\text{const}_\Pi$  denotes the space of functions constant in the fibers  $X_y$ .

**Warning:** One could bring the  $\delta$ -radii closer to the radii of  $X/\Pi$  above by evaluating them for the  $\delta$ -fibers  $X' \subset X$  with *normalized* measures and then sending  $\delta \rightarrow 0$ . Thus, we recapture the (radii of the) fibers themselves.

This works very well for  $X = Y \times Z \xrightarrow{p} Y$ , but it fails for more general  $p$  such as the Hopf fibration  $p : S^{2n+1} \rightarrow \mathbb{C}\mathbb{P}^n$ . Here, the  $\delta$ -radii with normalized measures are about  $\pi/2 = \frac{1}{2} \text{diam } S^1$  for  $\delta$  approaching zero, while the radii of  $S^{2n+1}/\Pi$  for the partition into the fibers  $p^1(y)$ ,  $y \in \mathbb{C}\mathbb{P}^n$ , can only be *smaller* than the corresponding absolute radii of  $S^{2n+1}$ . The latter, as we know, go to zero as  $n \rightarrow \infty$ , while the  $\delta$ -radii (with the normalized measure!) remain  $\geq \pi/2$ . The major reason why this happens is the *non*-precompactness of the family  $\{S^{2n+1}\}_{n \rightarrow \infty}$  in the  $\square_1$ -topology, but the geometry of the fibration is also important (compare [Gro–Mil]TAI).

**Remark:** The above shows that the concentration of  $X$  relative to a partition  $\Pi$  may be due to the concentration of all of  $X$  rather than to the concentration of the fibers. But, for example,  $[0, 1] \times S^{2n+1}$  partitioned into the Hopf circles does not fit either of these two possibilities. In fact, this may very well be the general case: the concentration relative to  $\Pi$  can always come from a fiberwise concentration of a coarser partition  $\Pi'$  of  $X$ .

**3½.49. Concentration  $X^n \rightarrow Y$  via maps  $p_n : X^n \rightarrow Y$ .** The discussion above gives a criterion for concentration (i.e.,  $\underline{H}_1 \mathcal{L}\ell_1$ -convergence)  $X^n$  to  $Y$  in terms of suitable maps  $p_n : X^n \rightarrow Y$ . Now we want to show that whenever a sequence of mm spaces  $X^n$  concentrates to some  $Y$  as  $n \rightarrow \infty$ , there exist maps  $p_n : X^n \rightarrow Y$  behaving in a manner similar to the projections  $Y \times Z^n \rightarrow Y$ , where  $\text{ObsDiam } Z^n \rightarrow 0$ . Here is our

**Proposition:** *A sequence  $X^n$  concentrates to  $Y$  if and only if there exist Borel measurable maps  $p_n : X^n \rightarrow Y$  with the following properties:*

**0.\*** *The pushforward measures  $(p_n)_*(\mu_{X^n})$  converge to  $\mu_Y$ . (Here we assume that our measures are finite,  $\mu(X^n) < \infty$  as well as  $\mu(Y) < \infty$ , and so the convergence of the measures implies that the masses  $m_n = \mu(X^n)$  converge to  $\mu(Y)$ .)*

**I\*.** *The maps  $p_n$  are 1-Lipschitz up to  $\varepsilon_n$ -errors, where  $\varepsilon_n \rightarrow 0$  as  $n \rightarrow \infty$ .*

**II\*.** *The fibers of the maps concentrate to points in the following sense*

$$\limsup_{n \rightarrow \infty} (\delta\text{-ObsDiam}(X^n/Y; -\kappa)) \leq \delta$$

*for all positive  $\delta$  and  $\kappa$ .*

**II\*.** *For every open subset  $B \subset Y$  of diameter  $D$ , the functions  $d(x) = \text{dist}(x, p_n^{-1}(B))$  and  $\underline{d}(x) = \text{dist}(p(x), B)$  eventually become  $D$ -close in the metric  $\text{me}_1$  on functions on  $X$ , i.e.*

$$\limsup_{n \rightarrow \infty} \text{me}_1(d, \underline{d}) \leq D.$$

**Sketch of the proof.** The “if” claim follows from the previous discussion, at least for  $(p_n)_*(\mu_{X^n}) = \mu_Y$ , and the general case requires a minor adjustment. (In fact, if  $\mu(X^n) = \mu(Y)$  and the spaces  $X^n$  have no atoms, then one can easily perturb the maps  $p_n$ , gaining the relation  $(p_n)_*(\mu_{X^n}) = \mu_Y$  without disturbing I\*, II\*, and III\*. A more interesting part is “only if,” which needs an actual construction of maps  $p_n$  given  $X^n$  concentrating to  $Y$ . To do this, let us look at what can be seen of a given mm space  $(X, \mu, \text{dist})$  on the Euclidean “screen”  $\mathbb{R}^N$  with the  $\ell_\infty$  metric. Our “observables” are 1-Lipschitz maps  $F: X \rightarrow \mathbb{R}^N$ , i.e.,  $N$ -tuples of 1-Lipschitz functions  $(f_1, \dots, f_N)$ , and what we see are the pushforward measures  $F_*(\mu)$  on  $\mathbb{R}^N$ . We denote by  $\mathcal{M}(X \xrightarrow{\text{Lip}_1} \mathbb{R}^N) \subset \mathcal{M}(\mathbb{R}^N)$  the subset of these measures for all 1 Lipschitz maps  $F: X \rightarrow (\mathbb{R}^N, \|\cdot\|_{\ell_\infty})$ , where  $\mathcal{M}(\mathbb{R}^N)$  denotes the space of all Borel measures on  $\mathbb{R}^N$  equipped with the  $\text{di}_1$ -metric.

**(A) Observational criterion for concentration.** *The following two conditions are equivalent:*

*(i) The  $X^n$  concentrate to  $Y$  as  $n \rightarrow \infty$ .*

*(ii) For every  $N = 1, 2, \dots$ , the subsets  $\mathcal{M}(X^n \xrightarrow{\text{Lip}_1} \mathbb{R}^N) \subset \mathcal{M}(\mathbb{R}^N)$  Hausdorff-converge to  $\mathcal{M}(Y \xrightarrow{\text{Lip}_1} \mathbb{R}^N) \subset \mathcal{M}(\mathbb{R}^N)$  as  $n \rightarrow \infty$ , where the Hausdorff convergence refers to the  $\text{di}_1$ -metric in  $\mathcal{M}(\mathbb{R}^N)$ .*

**Proof of (i)  $\Rightarrow$  (ii).** Recall that  $H_1$   $\mathcal{L}\ell_1$ -closeness between two spaces  $X$  and  $Y$  means that the spaces of 1-Lipschitz functions  $\mathcal{Lip}_1(X)$  and  $\mathcal{Lip}_1(Y)$  are Hausdorff close in the ambient space  $\mathcal{F}$  of functions with the  $\text{me}_1$ -metric on the parametrizing space  $[0, m]$ . Thus, for every  $N$ -tuple of 1-Lipschitz functions  $f_i$  on  $X$ , one can find functions  $f'_i$  on  $Y$  which are  $\text{me}_1$ -close in  $\mathcal{F}$  to the corresponding  $f_i$ , and therefore the pushforward measure  $F'_*(\mu_Y)$  on  $\mathbb{R}^N$  is  $\text{di}_1$ -close to the measure  $F_*(\mu_X)$ . This yields the implication (i)  $\Rightarrow$  (ii).

**Proof of (ii)  $\Rightarrow$  “only if”.** We use an approximation of  $Y$  by its Euclidean images  $\underline{Y}_N$  for 1-Lipschitz maps  $\Phi_N : Y \rightarrow (\mathbb{R}^N, \|\cdot\|_{\ell_\infty})$ , where  $\underline{Y}_N$  denotes  $(\mathbb{R}^N, \underline{\mu}_N, \|\cdot\|_{\ell_\infty})$  with  $\underline{\mu}_N = (\Phi_N)_*(\mu_Y)$  (see 3½.17). Such a  $\underline{Y}_N$  can be chosen arbitrarily  $\square_1$ -close to  $X$  for large  $N$ , and thus we have approximate inverse maps  $\Psi_N : \underline{Y}_N \rightarrow Y$ . On the other hand, according to (ii), each  $\underline{\mu}_N$  can be arbitrarily closely  $\text{di}_1$ -approximated by measures  $\mu'(n) = \Phi'_*(\mu_{X^n})$  for large  $n = n(N)$ , where  $\Phi' = \Phi'_N(\Phi)$  are some 1-Lipschitz maps  $X^n \rightarrow \mathbb{R}^N$ . Then one can slightly modify the approximate inverse maps,  $\Psi_N \rightsquigarrow \Psi' : \mathbb{R}^N \rightarrow Y$ , such that these  $\Psi' = \psi'_{N,r}$  will be 1-Lipschitz up to  $\varepsilon = \varepsilon(n, N)$  for the measure  $\mu'(n)$  and send  $\mu'(n)$   $\varepsilon$  close to  $\mu_Y$  on  $Y$ , where  $\varepsilon \rightarrow 0$  as  $N \rightarrow \infty$  and  $n = n(N) \rightarrow \infty$ . This can be done, for example, by  $\delta$ -regularizing the map  $\Psi_N$ , i.e., by taking  $\Psi_{N,\delta}$  which is defined in the  $\delta$ -neighborhood  $U_\delta = U_\delta(\text{Supp}(\underline{\mu}_N))$ , and which sends each  $u \in U_\delta$  close to the majority of points in the  $\Psi_N$ -image of the ball of radius  $\delta$  around some point  $v \in \text{Supp } \mu_N$  which is  $\delta$ -close to  $u$ . We leave the quantification of this (which is fairly easy) to the reader.

Finally, we compose  $\Phi'$  and  $\Psi'$ , thus getting a maps  $p = p_n = \Psi' \circ \Phi' : X^n \rightarrow Y$  which are 1-Lipschitz up to  $\varepsilon'$  and which send  $\mu_{X^n}$   $\varepsilon'$ -close to  $\mu_Y$ , where  $\varepsilon' \rightarrow 0$  as  $n \rightarrow \infty$ . These maps are good for  $0^*$  and  $I^*$  in the proposition above, and now we claim that the automatically satisfy  $II^*$  and  $III^*$ .

**(9) Lemma:** Let  $X^n$  be a sequence of mm spaces such that the metric spaces  $(\mathcal{Lip}_1(X^n), \text{me}_1)$  Hausdorff-converge to the space  $(\mathcal{Lip}_1(Y), \text{me}_1)$  for some mm space  $Y$  of finite mass. Let  $p_n : X^n \rightarrow Y$  be a sequence of maps satisfying  $0^*$  and  $I^*$  of our Proposition. Then  $II^*$  and  $III^*$  are satisfied as well.

**Proof.** The properties  $0^*$  and  $I^*$  show that the maps  $p^*$  almost isometrically, up to error  $\varepsilon_n \rightarrow 0$ , send  $\mathcal{Lip}_1(Y)$  to the  $\varepsilon_n$ -neighborhood of  $\mathcal{Lip}_1(X^n)$ , while  $II_A^*$  and  $II_B^*$  say, in effect, that the  $\varepsilon'_n$ -neighborhood of the image  $p^*(\mathcal{Lip}_1(Y))$  contains  $\mathcal{Lip}_1(X^n)$  with  $\varepsilon'_n \rightarrow 0$ . One may  $\varepsilon_n$ -perturb the maps to make them send  $\mathcal{Lip}_1(Y)$  to  $\mathcal{Lip}_1(X_n)$ , invoke the compactness of

$\mathcal{Lip}_1(Y)$ , and apply the following trivial

**Sublemma:** *Let a sequence of metric spaces  $\mathcal{L}_n$  Hausdorff-converge to a compact metric space  $\mathcal{L}$ , and let  $q_n : \mathcal{L} \rightarrow \mathcal{L}_n$  be Borel maps such that*

$$\text{dist}(q_n(\ell), q_n(\ell')) \geq \text{dist}(\ell, \ell') - \varepsilon_n$$

*for  $\varepsilon_n \rightarrow 0$ ,  $n \rightarrow \infty$ . Then the images  $q_n(\mathcal{L}) \subset \mathcal{L}_n$  are  $\varepsilon'_n$ -dense for  $\varepsilon'_n \rightarrow 0$ ,  $n \rightarrow \infty$ .*

In fact, this is seen by looking at maximal  $\delta$ -separated nets  $N_\delta \subset \mathcal{L}$  for  $\delta = \delta_n \rightarrow 0$  as it is done in showing that every distance increasing self-mapping of a compact metric space  $\mathcal{L}$  into itself is a surjective isometry.

**Proof of (ii)  $\Rightarrow$  (i).** The Hausdorff convergence  $\mathcal{M}(X^n \rightarrow \mathbb{R}^N) \rightarrow \mathcal{M}(Y \rightarrow \mathbb{R}^N)$  trivially implies that the “curvatures”  $K_N(\mathcal{Lip}_1(X^n)) \subset M_N = \mathbb{R}^{N(N-1)/2}$  converge to  $K_N(\mathcal{Lip}_1(Y)) \subset M_N$  in the Hausdorff topology of subsets in  $M_N$ . This yields (see Ch. 3.D<sub>+</sub>) the Hausdorff convergence  $\mathcal{Lip}_1(X^n) \rightarrow \mathcal{Lip}_1(Y)$  and the argument above using the lemma applies.

**(10) Concentration  $X^n \rightarrow Y$  as an ergodic decomposition.** When  $n$  is “infinitely large” and  $X^n$  “infinitely concentrates” to  $Y$ , this essentially amounts to  $X^n$  being decomposed into “infinitely concentrated” pieces which are the fibers of a suitable map  $X^n \rightarrow Y$ . This is vaguely similar to the decomposition of a measurable transformation into ergodic components (compare 3.42(7)). On the other hand, if  $\alpha : M \rightarrow M$  is an automorphism of a measure space  $M$  and  $f : M \rightarrow X$  is a measurable map to a metric space  $X$ , one can look at the maps  $f_n = (f, \alpha \circ f, \dots, \alpha^{n-1} \circ f) : M^n \rightarrow X^n$ , give  $X^n$  some (say  $\ell_p$ ) product metric  $\text{dist} \times \text{dist} \times \dots \times \text{dist}$  and the measure  $(f_n)_*(\mu \times \mu \times \dots \times \mu)$ . Then one can relate the ergodic decomposition of  $\alpha$  to some concentration of  $X^n$  or rather of  $\lambda_n X^n$  with  $\lambda_n = o(1)$ . We suggest that the reader look at specific instances of this picture).

## I. The Lipschitz order on $\mathcal{X}$ , pyramids, and asymptotic concentration

Recall the order relation  $A \prec B$  for mm spaces referring to a 1 Lipschitz map  $B \rightarrow A$  sending  $\mu_B$  to  $c\mu_A$  with  $c \geq 1$  (see 3 $\frac{1}{2}$ .15). Then for a sequence (of mm spaces)  $X^n \in \mathcal{X}$ ,  $n = 1, 2, 3, \dots$ , we define its *tail*  $T\{X^n\} \subset \mathcal{X}$  as the set of the limits of the  $\square_1$ -convergent sequences  $Y_n \in \mathcal{X}$ , where each  $Y_n$  is Lipschitz dominated by some  $X^n$ , i.e.,  $Y_n \prec X^n$ . Notice that every infinite subsequence  $X^{n_i}$  has a bigger tail  $T\{X^{n_i}\} \supset T\{X^n\}$ .

**3½.50. Proposition.** *If  $X^n$  concentrate to  $Y$ , then  $Y$  serves as the maximal element in the tail of  $\{X^n\}$ , i.e.,  $Y \in T\{X^n\}$  and  $Y \succ Y'$  for all  $Y' \in T\{X^n\}$ . Conversely, if  $T\{X^n\}$  admits a (necessarily unique) maximal element  $Y$ , then  $X^n$  concentrate to  $Y$  provided that every infinite subsequence  $X^{n_i}$  of  $X^n$  has  $T\{X^{n_i}\} = T\{X^n\}$ .*

**Proof.** If  $X^n$  concentrate to  $Y$ , then  $Y$  equals the  $\sqsubseteq_1$ -limit of some Euclidean 1-Lipschitz images of  $X^n$  approximating images of  $Y$  in  $(\mathbb{R}^N, \|\cdot\|_{\ell_\infty})$  for  $N \rightarrow \infty$  and  $n = n(N) \rightarrow \infty$  as follows from (A). And every  $Y' \in T\{X^n\}$  is also a limit of such images of  $X^n$  in  $\mathbb{R}^{N_n}$ , and so it appears as the  $\sqsubseteq_1$ -limit of approximating images of  $Y$  in  $\mathbb{R}^{N_n}$  as again follows from (A). Then  $Y \succ Y'$  by the  $\sqsubseteq$ -continuity of the Lipschitz order. Notice that this equally applies to  $Y' \in T\{X^{n_i}\}$  for every infinite subsequence  $X^{n_i}$  and shows, in particular, that  $T\{X^{n_i}\} = T\{X^n\}$ .

Conversely, let  $Y \in T\{X^n\}$  dominate all tails  $T\{X^{n_i}\}$ . Then it dominates the limits of images of  $X^{n_i}$  in  $\mathbb{R}^N$  for  $i \rightarrow \infty$  and every  $N$ . Since  $Y$  lies in  $T\{X^n\}$ , all of its images in  $\mathbb{R}^N$  can be approximated by those of  $X^n$  for  $n \rightarrow \infty$ , and so  $X^n$  concentrates by (A) again.

**3½.51. Pyramids in  $\mathcal{X}$  and their local Hausdorff convergence.** A subset  $\mathcal{P} \subset \mathcal{X}$  is called a *pyramid* if

- (a)  $\{X \in \mathcal{P} \text{ and } Y \prec X\} \Rightarrow Y \in \mathcal{P}$ ,
- (b) for every pair  $X, X' \in \mathcal{P}$ , there exists  $Y \in \mathcal{P}$  dominating  $X$  and  $X'$ , i.e., such that  $Y \succ X$  and  $Y \succ X'$ .

**Example of  $\mathcal{P} = \mathcal{P}_X$ .** This denotes the pyramid with *apex*  $X \in \mathcal{X}$ , i.e.,

$$\mathcal{P}_X \stackrel{\text{def}}{=} \{X' \in \mathcal{X} : X' \prec X\}.$$

Clearly, this  $\mathcal{P}_X$  is a  $\sqsubseteq_1$ -closed subset in  $\mathcal{X}$  (see 3.41(3)(b)). Furthermore, if  $X$  and  $X'$  are  $\sqsubseteq_1$ -closed in  $\mathcal{X}$ , then their pyramids  $\mathcal{P}_X$  and  $\mathcal{P}_{X'}$  are closed with respect to the Hausdorff metric corresponding to  $\sqsubseteq_1$  in  $\mathcal{X}$ . In particular,  $\sqsubseteq_1$ -convergence  $X^n \rightarrow Y$  implies the Hausdorff convergence  $\mathcal{P}_{X^n} \rightarrow \mathcal{P}_Y$ .

Next, we invoke the following general notion of *local Hausdorff convergence* of subsets  $\mathcal{Y}_i$  in a metric space  $\mathcal{X}$ , e.g., in our  $(\mathcal{X}, \text{dist} = \sqsubseteq_1)$ . We assign to each subset  $\mathcal{Y} \subset \mathcal{X}$  the distance function  $d_{\mathcal{Y}}(X) = \text{dist}(X, \mathcal{Y})$  for all  $X \in \mathcal{X}$  and observe that the ordinary Hausdorff convergence  $\mathcal{Y}_i \rightarrow \mathcal{Y}$  amounts to the *uniform* convergence of functions  $d_{\mathcal{Y}_i} \rightarrow d_{\mathcal{Y}}$ . Then we say that  $\mathcal{Y}_i$  locally (Hausdorff) converge to  $\mathcal{Y}$  if

- (a)  $d_{\mathcal{Y}_i}(Y) \rightarrow 0$  for each  $X$  where  $d_{\mathcal{Y}}(X) = 0$ , and
- (b)  $\liminf_{i \rightarrow \infty} d_{\mathcal{Y}_i}(X) > 0$  whenever  $d_{\mathcal{Y}}(X) > 0$ .

**Example:** If the functions  $d_{\mathcal{Y}_i}$  converge to  $d_{\mathcal{Y}}$  at each point  $X \in \mathcal{X}$ , then  $\mathcal{Y}_i$  locally converge to  $\mathcal{Y}$ . Notice that since the functions  $d_{\mathcal{Y}_i}$  are all 1-Lipschitz, pointwise convergence implies uniform convergence on each compact subset in  $\mathcal{X}$ . This motivates our “local” terminology. Also observe that if  $\mathcal{X}$  is a *proper* metric space, i.e., all closed balls  $B(R)$  in  $\mathcal{X}$  for  $R < \infty$  are *compact*, then (a) and (b) imply pointwise convergence of  $d_{\mathcal{Y}_i}$  to  $d_{\mathcal{Y}}$  (and we suggest that the reader make up an example showing that this is false for nonproper spaces).

**Down-to-earth criterion for local convergence.** *If  $\mathcal{Y}$  is a closed subset in  $\mathcal{X}$  and  $\mathcal{Y}_i$  locally converge to  $\mathcal{Y}$ , then  $\mathcal{Y}$  equals the set of limits of all convergent subsequences  $Y_i \in \mathcal{Y}_i$ . Furthermore, every convergent sequence  $Y_j \in \mathcal{Y}_{i_j}$  with  $i_j \rightarrow \infty$  for  $j \rightarrow \infty$  has its limit contained in  $\mathcal{Y}$ . Conversely, if  $\mathcal{Y}$  consists of the limits of all convergent sequences  $Y_i \in \mathcal{Y}_i$  and every convergent sequence  $Y_j \in \mathcal{Y}_{i_j}$  has  $\lim_{j \rightarrow \infty} Y_j \in \mathcal{Y}$ , provided that  $i_j \rightarrow \infty$ , then the sequence  $\mathcal{Y}_i$  locally converges to  $\mathcal{Y}$ .*

The proof is straightforward and is left to the reader. Now the proposition above yields the following theorem

**“Pyramidal” criterion for concentration.** *A sequence  $X^n \in \mathcal{X}$ ,  $n = 1, 2, \dots$ , concentrates (i.e.,  $\underline{H}_1 \mathcal{L}\ell_1$ -converges) to  $Y$  if and only if the corresponding pyramids  $\mathcal{P}_X \subset \mathcal{X}$  weakly-converge to  $\mathcal{P}_Y$  for the metric  $\square_1$  in  $\mathcal{X}$ .*

**3 $\frac{1}{2}$ .52.** This suggests looking at the space  $\Pi \supset \mathcal{X}$  of all  $\square_1$ -closed pyramids  $\mathcal{P}$  in  $\mathcal{X}$ , where  $\mathcal{X}$  is embedded into  $\Pi$  via  $X \mapsto \mathcal{P}_X$ . Clearly, every closed pyramid  $\mathcal{P}$  appears as the  $\square_1$ -closure of an increasing union of  $\mathcal{P}_{X_i}$  for  $i = 1, 2, \dots$ , where  $X_1 \prec X_2 \prec \dots \prec X_i \prec \dots$ , and so  $\mathcal{P}_{X_1} \subset \mathcal{P}_{X_2} \subset \dots \subset \mathcal{P}_{X_i} \subset \dots$ . Thus, closed pyramids  $\mathcal{P} \in \Pi \supset \mathcal{X}$  can be viewed as “ideal limits” of increasing sequences of mm spaces  $X_1 \prec X_2 \prec \dots$ . In fact, it is convenient to consider more general

**Asymptotic sequences.** We call a sequence  $X_i \in \mathcal{X}$  *asymptotic* if the corresponding pyramids  $\mathcal{P}_{X_i}$  weakly converge to some (pyramid)  $\mathcal{P} \in \Pi$ . Intuitively, a sequence  $X_i$  is asymptotic if it displays definite asymptotic behavior as  $i \rightarrow \infty$ . Clearly, every sequence  $X_i$  admits an asymptotic subsequence. In fact, if  $\mathcal{X}$  is an arbitrary Polish space, then every sequence  $\mathcal{Y}_i \subset \mathcal{X}$  admits a weakly Hausdorff-convergent subsequence. Moreover, there (obviously) exists a subsequence  $\mathcal{Y}_{i_j}$  such that the distance functions  $d_j = d_j: X \mapsto \text{dist}(X, \mathcal{Y}_{i_j})$  converge at each point  $X \in \mathcal{X}$  for  $j \rightarrow \infty$ .

**Exercises:** Show that the sequence  $S^n(\sqrt{n})$ ,  $n = 1, 2, \dots$ , is asymptotic.

Compare the limit pyramids for the spheres  $S^n(\sqrt{n})$  and the Gaussian spaces  $(\mathbb{R}^n, e^{-\|x\|^2} dx)$ . Study the limit pyramid for the cartesian powers  $X^n = X \times \dots \times X$  of a given mm space  $X$ , e.g.,  $X = [0, 1]$ , with the  $\ell_p$ -product metric.

**Local convergence via  $\mathcal{X}(N, R)$ .** Let  $\mathcal{X}(N, R) \subset \mathcal{X}$  denote the subset of those mm spaces  $X$  which correspond to measures in the  $R$ -ball in  $(\mathbb{R}^N, \|\cdot\|_{\ell_\infty})$ , i.e., of  $X$  isomorphic to  $(\mathbb{R}^N, \|\cdot\|_{\ell_\infty})$  with a measure supported in the  $R$ -ball. Clearly  $\mathcal{X}(N, R)$  is a compact subset in  $\mathcal{X}$ , and, by the approximation argument above,  $\mathcal{X}$  equals the closure of the union  $\bigcup_{N=1}^\infty \mathcal{X}(N, N)$ . Furthermore, every pyramid  $\mathcal{P}$  in  $\mathcal{X}$  equals the  $\sqsubseteq_1$ -closure of the union  $\bigcup_{N=1}^\infty (\mathcal{P} \cap \mathcal{X}(N, N))$ . It follows that

$\mathcal{P}_i$  weakly converge to  $\mathcal{P}$  as  $i \rightarrow \infty$  if and only if

$$\mathcal{P}_i \cap \mathcal{X}(N, N) \xrightarrow{\text{Hau}} \mathcal{P} \cap \mathcal{X}(N, N)$$

for each  $N = 1, 2, \dots$ , where the Hausdorff convergence refers to that for subsets in the space  $\mathcal{X}(N, N)$  with the  $\sqsubseteq_1$ -metric.

**3½.53. Asymptotic concentration and the  $\underline{H}_1 \mathcal{L}_{\ell_1}$  completion  $\overline{\mathcal{X}}$  of  $\mathcal{X}$ .** We say that a sequence  $X_i \in \mathcal{X}$  asymptotically concentrates if it Cauchy-converges with respect to the metric  $\underline{H}_1 \mathcal{L}_{\ell_1}$  on  $\mathcal{X}$ . The proof of (i)  $\Rightarrow$  (ii) in 3½.50(A) shows that

if a sequence  $X_i$  asymptotically concentrates, then it is asymptotic.

Thus, every point  $Y$  in the  $\underline{H}_1 \mathcal{L}_{\ell_1}$ -completion of  $\mathcal{X}$ , denoted  $\overline{\mathcal{X}}^{\underline{H}_1 \mathcal{L}_{\ell_1}}$  is represented by a (unique) pyramid  $\mathcal{P} = \mathcal{P}_Y \subset \mathcal{X}$  which is the weak limit of  $\mathcal{P}_{X_i}$ . Notice that  $\mathcal{P}_Y$  is  $\sqsubseteq_1$ -closed in  $\mathcal{X}$ . Therefore, it is  $\underline{H}_1 \mathcal{L}_{\ell_1}$ -closed. In fact,

every  $\sqsubseteq_1$ -closed pyramid  $\mathcal{P}$  in  $\mathcal{X}$  is obviously weakly closed,

where ‘‘weakly closed’’ means that if pyramids  $\mathcal{P}_i \subset \mathcal{P}$  weakly converge to some  $\mathcal{P}'$ , then  $\mathcal{P}' \subset \mathcal{P}$ . And, *weakly closed*  $\Rightarrow$   $\underline{H}_1 \mathcal{L}_{\ell_1}$ -closed by the previous discussion. It is also clear that

$$\mathcal{P}_Y = \mathcal{P}_{Y'} \quad \Rightarrow \quad Y = Y'$$

for arbitrary  $Y$  and  $Y'$  in  $\overline{\mathcal{X}}^{\underline{H}_1 \mathcal{L}_{\ell_1}}$ . In other words, the map  $\overline{\mathcal{X}}^{\underline{H}_1 \mathcal{L}_{\ell_1}} \rightarrow \Pi$  given by  $Y \mapsto \mathcal{P}_Y$  is one to-one. This is seen with the following criterion for asymptotic concentration  $X_i \xrightarrow{\underline{H}_1 \mathcal{L}_{\ell_1}} Y$ .

Denote by  $\mathcal{M}_i = \mathcal{M}_i(N, R)$  the set of pushforward measures in the  $R$ -ball  $B(R) \subset \mathbb{R}^N$  under 1-Lipschitz maps  $X_i \rightarrow B(R)$ , where  $B(R)$  comes along with the  $\ell_\infty$ -metric. Then, we introduce a set of measures on  $B(R) \subset \mathbb{R}^N$  associated to  $\mathcal{P} = \mathcal{P}_Y$  and denoted by  $\mathcal{M} = \mathcal{M}(Y; N, R)$ , which equals the set of those  $\mu$  for which  $(B(R), \mu)$  is isomorphic to some  $X \in \mathcal{P} \cap \mathcal{X}(R, N)$ .

**Observational criterion for asymptotic concentration.** *A sequence  $X_i \in \mathcal{X}$  asymptotically concentrates to  $Y \in \overline{\mathcal{X}}^{H\mathcal{L}^\iota}$  iff  $\mathcal{M}_i$  Hausdorff-converge to  $\mathcal{M}$  for every  $N \in \mathbb{N}$  and  $R \geq 0$ .*

The proof is identical to that above (using 3 $\frac{1}{2}$ .50(A)) and is left to the reader.

Finally, we close the circle by calling a pyramid  $\mathcal{P}$  concentrated if the metric spaces  $\mathcal{L} = (\text{Lip}_1(X), \text{me}_1)$  for all  $X \in \mathcal{P}$  form a precompact family in the Hausdorff sense.

**Proposition:** *A pyramid  $\mathcal{P}$  is concentrated iff it is of the form  $\mathcal{P} = \mathcal{P}_Y$  for some  $Y \in \overline{\mathcal{X}}^{H\mathcal{L}^\iota}$ . This  $Y$  is unique, and we say that “ $\mathcal{P}$  concentrates to  $Y$ .”*

**Proof.** Given two  $\mathcal{L}$  and  $\mathcal{L}'$  as above, i.e., of the form  $\text{Lip}_1(X)$  and  $\text{Lip}_1(X')$  for  $X, X' \in \mathcal{P}$ , we can make yet another space  $\mathcal{L}''$  corresponding to  $X''$  Lipschitz dominating  $X$  and  $X'$  and thus isometrically containing both  $\mathcal{L}$  and  $\mathcal{L}'$ . It follows that whenever a sequence  $X_i \subset \mathcal{P}$  represents  $\mathcal{P}$ , in the sense that the  $\mathcal{P}_{X_i}$  weakly converge to  $\mathcal{P}$ , then  $\mathcal{L}_i = \text{Lip}_1(X_i)$  Hausdorff-converge to some space  $\mathcal{L}$ , and by the logic of the proof of (ii)  $\Rightarrow$  (i) (see 3 $\frac{1}{2}$ .50), the spaces  $X_i$  asymptotically concentrate to some  $Y$  such that  $\mathcal{P}_Y = \mathcal{P}$ . (We leave the details to the reader.)

**3 $\frac{1}{2}$ .54. About the map  $\overline{\mathcal{X}} \rightarrow \mathcal{H}(= \mathcal{X}_c)$ .** Let  $\mathcal{H}$  denote the Hausdorff moduli space of compact metric spaces (which was called  $\mathcal{X}_c$  in 3.11 $\frac{1}{2}_+$ ). Then the space  $\overline{\mathcal{X}} = \overline{\mathcal{X}}^{H\mathcal{L}^\iota}$  naturally goes to  $\mathcal{H}$  for  $X \mapsto (\text{Lip}_1(X), \text{me}_1)$ . This map is first defined on  $\mathcal{X} \subset \overline{\mathcal{X}}$ , and then it extends to all of  $\overline{\mathcal{X}}$  by continuity with respect to the  $\underline{H}_1 \mathcal{L}^\iota$  metric, since  $\mathcal{X}$  is dense in  $\overline{\mathcal{X}}$ .

*The (obviously continuous) map  $\overline{\mathcal{X}} \rightarrow \mathcal{H}$  is proper, i.e., preimages of compact sets are compact.*

In fact, let  $X_i \in \mathcal{X}$  satisfy  $\text{Lip}_1(X_i) \xrightarrow{\text{Hau}} \mathcal{L}$ . Then we may assume without loss of generality that the sequence  $\mathcal{X}_i$  is asymptotic (since we can always pass to a subsequence), and so the  $\mathcal{P}_{X_i}$  weakly converge to some pyramid  $\mathcal{P}$ . This clearly is concentrated, hence the  $X_i$  concentrate to some  $Y \in \overline{\mathcal{X}}$ , and our claim follows. (Again the details are left to the reader.)

**Question:** Is our map  $\overline{\mathcal{X}} \rightarrow \mathcal{H}$  one-to-one?

**3½.55. About the embedding  $\overline{X} \rightarrow \Pi$ .** The space  $\Pi$  of all pyramids  $\mathcal{P} \subset \mathcal{X}$  is clearly compact, and the map  $\overline{\mathcal{X}} \rightarrow \Pi$  defined by  $Y \mapsto \mathcal{P}_Y$  is continuous for the  $\underline{H}_1 \mathcal{L}\iota_1$  metric in  $\overline{\mathcal{X}}$  and the topology of weak convergence in  $\Pi$ . This is immediate with all we have seen at this stage. Furthermore, this map is injective, as we have mentioned earlier. An additional remark we now wish to make is that this injective map is a *topological embedding*, i.e.,

the weak convergence  $\mathcal{P}_{Y_i} \rightarrow \mathcal{P}_Y$  implies  $\underline{H}_1 \mathcal{L}\iota_1$ -convergence  $Y_i \rightarrow Y$ .

This is a mild generalization of the proposition above whose proof is left to the reader.

Now, all of the concentration discussion is expressed in the “pyramidal” language with the exception of the Hausdorff compactness criterion distinguishing  $\overline{\mathcal{X}} \subset \Pi$ , where we need the map  $\mathcal{X} \rightarrow \mathcal{H}$  given by  $X \mapsto (\mathcal{Lip}_1(X), \text{me}_1)$ .

**3½.56. Basic example of asymptotic concentration.** Consider partial cartesian products  $X_i = F_1 \times F_2 \times \cdots \times F_i$  for some infinite sequence of mm spaces  $F_i$  of finite mass. If the observable diameters of the “tails”  $\Phi_{ij} = F_i \times F_{i+1} \times \cdots \times F_j$  satisfy

$$\text{ObsDiam}(\Phi_{ij}, -\kappa) \rightarrow 0$$

for each  $\kappa > 0$  and  $i, j \rightarrow \infty$ , then the  $X_i$  clearly asymptotically concentrate, and the limit  $Y \in \overline{\mathcal{X}}$  is represented by the infinite product  $F_1 \times F_2 \times \cdots \times F_i \times \cdots$ , which is a kind of “ideal mm space.” An especially attractive instance of this is where the  $F_i$  are Riemannian manifolds with  $\lambda_1(F_i) \rightarrow \infty$ , such as the unit Euclidean spheres  $S^i$ , where we can bound  $\text{ObsDiam}_{\mathbb{R}}(\Phi_{ij})$  in terms of  $\lambda_1(\Phi_{ij}) = \sup_{j \geq i} \lambda_1(F_j)$  (compare 3½.62).

**3½.57. Spectral criterion for asymptotic concentration.** Let us invoke the space  $\text{Dir}_1 = \text{Dir}_1(X)$  of Lipschitz functions  $f$  on  $X$  satisfying  $\int_X \|\text{grad } f\|^2 d\mu \leq 1$  and look at the behavior of the metric spaces  $(\text{Dir}_1(X), \|\cdot\|_{L_2})$  as  $X$  runs over some pyramid  $\mathcal{P} \subset \mathcal{X}$ .

*Spectral concentration.* Call  $\mathcal{P}$  *spectrally concentrated* if for each  $X \in \mathcal{P}$ , the intersection of  $\text{Dir}_1(X)$  with the  $L_2$ -ball

$$L_2 B_1(X) = \left\{ f : \int_X f^2(x) d\mu_x \leq 1 \right\},$$

is compact with respect to the  $L_2$ -metric, and the totality of these inter-

sections

$$\{\text{Dir}_1(X) \cap L_2 B_1(X), \|\cdot\|_{L_2}\}$$

for  $X \in \mathcal{P}$  is Hausdorff precompact.

Observe that the  $L_2$ -compactness of  $\text{Dir}_1 \cap L_2 B_1$  is equivalent to the discreteness of the spectrum of the Laplace operator on  $X$ , which can be understood in the usual way if  $X$  is a Riemannian manifold and the Dirichlet functional

$$f \mapsto \text{Dir}(f) = \int_X \|\text{grad}(f)\|^2 d\mu$$

is quadratic. (This can be extended to the non-Riemannian case with the formalism described in 3½.39). Similarly, Hausdorff precompactness of a family  $\{\text{Dir}_1(X) \cap L_2 B_1(X), \|\cdot\|_{L_2}\}$  means, in the Riemannian case, a uniform bound on the number of eigenvalues in every fixed interval  $[0, \lambda]$ .

Also notice a certain discrepancy between the asymptotic concentration defined via  $(\text{Lip}_1(X), \text{me}_1)$  and the spectral one using  $(\text{Dir}_1(X), \|\cdot\|_{L_2})$ . Namely, in the former case, we did *not* intersect  $\text{Lip}_1$  with the unit  $L_\infty$ -ball of functions. Consequently, if, for example,  $X_i$  consists of two atoms of fixed mass with mutual distance  $i$ , then the sequence  $X_i$ ,  $i \rightarrow \infty$ , does *not* asymptotically concentrate with our convention, but it does concentrate spectrally. More generally, the asymptotic concentration excludes the possibility  $\text{ObsDiam}_{\mathbb{R}}(X; -\kappa) \rightarrow \infty$  for some  $\kappa > 0$ , while spectral concentration allows *finitely* many pieces of  $X$  of definite mass drifting far away from each other. Yet, we have the following trivial

**Proposition:** *Let  $\{X\}$  be a family of mm spaces with the following three properties:*

- (a) *The masses of all our  $X$ 's are bounded by a fixed constant  $< \infty$ .*
  - (b)  *$\text{diam}(X; m - \kappa) \leq \text{const}_\kappa < \infty$  for all  $\kappa > 0$ . (This means that there exist subsets  $X_\kappa \subset X$  with  $\text{diam } X_\kappa \leq \text{const}_\kappa$  and  $\mu(X \setminus X_\kappa) \leq \kappa$ .)*
  - (c) *The family  $\{\text{Dir}_1(X) \cap L_2 B_1(X), \|\cdot\|_{L_2}\}$  is Hausdorff precompact.*
- Then the family  $\{\text{Lip}_1(X), \text{me}_1\}$  is also Hausdorff precompact.*

**Proof.** To clarify the ideas, assume that  $\text{diam } X \leq D$  for all our  $X$  and let  $\bar{m} = \sup_{\{X\}} \mu(X)$ . Then every Lipschitz function  $f$  on  $X$  vanishing at some point  $x_0 \in X$  clearly has  $\|f\|_{L_2} \leq \bar{m}D^2$ , and so it is contained in the slightly enlarged set  $\text{Dir}_1 \cap L_2 B_1$ , namely in  $\bar{m}\text{Dir}_1(X) \cap \bar{n}L_2 B_1(X)$  for  $\bar{n} = \bar{m}D^2$ . On the other hand, the  $L_2$ -metrics dominate  $\text{me}_1$  by the Chebyshev inequality, and our proposition follows, since we can make every  $f$  vanish at  $x_0$  by adding a constant which does not affect relevant Hausdorff distances. Finally, we observe that the very nature of the metric  $\text{me}_1$  allows

us to throw away subsets of small measure  $\kappa$ , and so we can use (b) instead of the stronger assumption  $\text{diam}(X) \leq D$ . (The details are left to the reader.)

By specializing the proposition to pyramids and to (monotone) sequences of spaces, we immediately obtain the following

**Corollaries:** (i) *If a pyramid  $\mathcal{P}$  is spectrally concentrated, then it is concentrated provided that (a) and (b) hold for all  $X \in \mathcal{P}$ .*

(ii) *Let  $X_i$  be a sequence of Riemannian manifolds satisfying (a) and (b) and such that the number of eigenvalues of the Laplace operator on  $X_i$  in each interval  $[0, \lambda]$  is bounded by a constant  $c_\lambda < \infty$  independent of  $i$ . Then  $X_i$  admits an infinite subsequence which asymptotically concentrates. Furthermore, if the  $X_i$  are Lipschitz monotone increasing,  $X_1 \prec X_2 \prec \dots$ , then they asymptotically concentrate themselves.*

**Remark:** Spectral concentration is a by far more restrictive condition than asymptotic concentration. Thus, the “ideal apex” of a spectrally concentrated pyramid may carry far more interesting (spectral) geometry than a general “limit space”  $Y \in \overline{\mathcal{X}}$ . The first example to look at is the infinite product  $F_1 \times F_2 \times \dots$  considered in the previous section.

**Exercises:** (A) Sharpen (a) or (b) in the proposition by making them necessary for the asymptotic concentration for as well as sufficient in conjunction with (c).

(B) Let  $X_i$  be a sequence of Riemannian manifolds of unit mass satisfying  $\lambda_k(X_i) \rightarrow \infty$  as  $i \rightarrow \infty$  for some  $k$ . In other words, for each  $\lambda > 0$ , the spectrum of  $\Delta_{X_i}$  contains at most  $k$  points in  $[0, \lambda]$  for  $i \geq i(\lambda)$  (where the points of the spectrum are counted with multiplicity). Show that the separation distance satisfies  $\text{Sep}(X_i; \kappa_0, \dots, \kappa_k) \rightarrow 0$  as  $i \rightarrow \infty$  and arbitrary  $\kappa_0, \dots, \kappa_k \geq 0$ . Then (following Alon and Milman), look at 1-Lipschitz functions  $f_i : X_i \rightarrow \mathbb{R}$  and observe that the pushforward measures  $\mu_i$  on  $\mathbb{R}$  concentrate to at most  $k$  points. Namely, there exist subsets  $I_i \subset \mathbb{R}$ , each consisting of the union of  $k$  intervals of length  $\varepsilon_i$ , such that  $\varepsilon_i \rightarrow 0$  as  $i \rightarrow \infty$  and  $\mu_i(I) \rightarrow 1$ .

(C) **Question:** Let  $X_i$  be Riemannian manifolds whose spectra converge to that of a fixed space  $X$ . Under what assumptions do the spaces  $X_i$  concentrate to  $X$ ? (Problem (B) above shows that it works for finite spaces  $X$ .) In any case, what can be said about asymptotic (i.e.,  $\underline{H}_1 \mathcal{L} \iota_1$ ) limit  $Y \in \overline{\mathcal{X}}$  of these  $X_i$ ? (One may strengthen the assumptions by bringing in the nonlinear spectra mentioned in 3½.39).

(D) Take a sequence of probability mm spaces  $F_1, F_2, \dots$  and let  $X_n = F_1 \times F_2 \times \dots \times F_n$ , where the metric on  $X_n$  is  $\ell_p$ , i.e.,

$$\left( \sum_{i=1}^n \text{dist}_i^p \right)^{1/p},$$

for some  $1 \leq p \leq \infty$ . Give a criteria for the following behavior:

- (i)  $\square_1$ -convergence of  $X_n$  (compare 3.38(6)(f) and (f')).
- (ii) Asymptotic concentration.
- (iii) Spectral concentration.

Consider specifically the case of  $F_i = (F, \lambda_i \text{dist}, \mu)$  as in 3.38(6)(f), and show that the  $X_n$  spectrally (and thus asymptotically) concentrate for  $p = 2$  if  $F$  is a compact Riemannian manifold with a normalized Riemannian measure  $\mu$  whenever  $\lambda_i \rightarrow 0$ . Show that this is also true for the Gaussian space  $F = (\mathbb{R}, |x - y|, e^{-\pi x^2} dx)$ .

(E) Consider (full) ellipsoids  $X_n$  with principal semiaxes  $a_i = a_i(n)$ ,  $i = 1, \dots, n$ , i.e.

$$X_n = \{x \in \mathbb{R}^n : \sum_{i=1}^n a_i^{-2} x_i^2 \leq 1\}$$

with normalized Euclidean measures and figure out the mode of concentration of  $X_n$  in terms of  $a_i(n)$  for  $n \rightarrow \infty$ . In particular, prove the Levy concentration of  $X_n$  (i.e., concentration to the one point space) for  $a_i = \varepsilon_i \sqrt{i}$ ,  $i = 1, \dots, n$  and  $n \rightarrow \infty$ , where  $\varepsilon_i \rightarrow 0$  for  $i \rightarrow \infty$ . Show that there is no asymptotic concentration for  $a_i = \sqrt{i}$ ,  $i = 1, \dots, \sqrt{n}$ , and  $n \rightarrow \infty$ , not even for any subsequence of  $X_n$ . But if, for example,  $a_i(n) = \varepsilon_i \sqrt{n}$ , where  $\varepsilon_i \rightarrow 0$  as  $i \rightarrow \infty$ , then the  $X_n$  asymptotically (and even spectrally) concentrate. Moreover, if  $\sum_{i=1}^{\infty} \varepsilon_i^2 < \infty$ , then the  $X_n$  concentrate to an actual mm space, namely to the Hilbert space with a Gauss measure on it. (Yet these  $X_n$  may easily  $\square_1$ -diverge.)

(F) Observe similar behavior of more general (convex) subsets in  $\mathbb{R}^n$  as well as in other Banach spaces  $X^n$  of dimension  $n \rightarrow \infty$ . In particular, look at

$$X_n = \{x \in \mathbb{R}^n : \sum_{i=1}^n a_i x_i^a \leq 1\}$$

where  $\mathbb{R}^n$  can be given some  $\ell_p$ -metric. Also study the boundaries of such convex sets with induced (Minkowski) measures and metrics.

## J. Concentration versus dissipation

A dissipative behavior (of a sequence) of mm spaces is the opposite to that of concentration. Here are specific

**3½.58. Definitions.** A sequence  $X_i$   $\delta$ -dissipates mass  $m$  if for large  $i \rightarrow \infty$  there are (arbitrarily) small pieces of  $X$  drifting  $\delta$ -far apart and adding up to mass  $m$ . That is,

$$\liminf_{i \rightarrow \infty} \text{Sep}(X_i; \kappa_0, \dots, \kappa_N) \geq \delta$$

for every fixed  $(N+1)$ -tuple of positive numbers  $\kappa_i$  satisfying  $\kappa_0 + \kappa_1 + \dots + \kappa_N \geq m$  (see 3½.30 for the definition of Sep). If all these  $X_i$  themselves have  $\mu(X_i) = m$ , we say that they are  $\delta$ -dissipating. More generally, a sequence  $X_i$  is called  $\delta$  dissipating if, for each  $m > 0$ , every subsequence of spaces  $Y_j \subset X_i$ , of masses  $m_j \geq m$   $\delta$ -dissipates mass  $m$ .

For example, if  $X_i$  is an asymptotic sequence with  $\mu(X_i) \xrightarrow{i \rightarrow \infty} m < \infty$ , then it  $\delta$  dissipates if and only if the (weak) limit pyramid  $\mathcal{P} = \lim_{i \rightarrow \infty} \mathcal{P}_{X_i}$  contains (the isomorphism class of) every mm space of mass  $\leq m$  and diameter  $\leq \delta$ . (The proof of this is straightforward.)

Finally,  $\{X_i\}$  is called *infinitely dissipating* if it  $\delta$  dissipates for all  $\delta > 0$ . This is equivalent for the  $X_i$  above to having

$$\mathcal{P} = \mathcal{X}.$$

Notice that the full negation of dissipation is weaker than concentration. Namely, a sequence  $X_i$  is called *nondissipating* if for every  $m, \delta > 0$ , there exists  $\kappa > 0$  such that the inequalities  $\text{Sep}(X_i; \kappa_0, \dots, \kappa_N) \geq \delta$  and  $\kappa_0 + \kappa_1 + \dots + \kappa_N \geq m$  imply that  $\sup_{0 \leq k \leq N} \kappa_k \geq \kappa$ , independently of  $i$ . In other words, no subsequence  $\delta$ -dissipates a mass  $m > 0$  unless  $\delta = 0$ .

**Example:** The unit Euclidean cubes  $[0, 1]^n \subset \mathbb{R}^n$ ,  $n = 1, 2, \dots$ , comprise a nondissipating family, but they do not asymptotically concentrate.

**Proof.** The nonconcentration is obvious. In fact, even if we use the smaller  $\ell_\infty$ -metric on  $I^n$ , the cubes still do not concentrate, since the  $n$  (1-Lipschitz) coordinate projections  $I^n \rightarrow \mathbb{R}$  make a *non precompact* family for the Hausdorff metric associated to  $\text{me}_1$ .

But on the other hand, the nondissipation follows from the bound  $\lambda_1([0, 1]^n) = \lambda_1([0, 1]) = \pi^2 > 0$  via the following lemmas.

**(A)** *If spaces  $X_i$  of masses  $\leq m \leq \infty$  have large expansion of subsets of small measure, namely*

$$\exp(X_i; \kappa, \rho) \geq e > 1 \tag{*}$$

for every  $i$ , each given  $\rho > 0$ , and  $0 < \kappa \leq \kappa(\rho)$ , then the sequence  $\{X_i\}$  does not dissipate.

Indeed  $(*)$  shows that the  $\delta$ -neighborhood of a subset  $Y \subset X_i$  of small mass  $\kappa$  has much greater mass than  $Y$  and our claim follows.

**(B)** If  $\lambda_1(X) \geq \varepsilon > 0$ , then the  $X_i$  satisfy the expansion property above.

This is a special case of 3 $\frac{1}{2}$ .38.

**3 $\frac{1}{2}$ .59. The subquotient order  $X \triangleleft Y$ .** This is defined by

$$X \triangleleft Y \quad \Leftrightarrow \quad X \prec Y' \subset Y,$$

i.e.,  $X$  is Lipschitz dominated by some *closed* subset  $Y' \subset Y$  with the metric and measure of  $Y$  restricted to  $Y'$ . (Little would change if we allowed arbitrary Borel subsets  $Y' \subset Y$ .) It is indeed a partial ordering, since (obviously)

$$X \triangleleft Y \triangleleft Z \quad \Leftrightarrow \quad X \triangleleft Z,$$

and (by an easy argument),

$$X \triangleleft Y, X \triangleright Y \quad \Leftrightarrow \quad X \simeq Y$$

in  $\mathcal{X}$ . A useful invariant of an mm space  $X$  is the totality of all spaces  $Y \triangleleft X$  consisting of at most  $k$  points,  $k = 1, 2, \dots, \infty$ , denoted  $F_k^{\triangleleft} X$ . These carry the same information as (the totality of) the measures  $\underline{\mu}_r^X$  (see 3.39) but are more appropriate for expressing the ideas of concentration and dissipation.

**Exercises:** (a) Reformulate the notions of dissipation above in terms of  $F_k^{\triangleleft}$ .

(b) Determine which of the invariants from 3 $\frac{1}{2}$ .F are monotone for the subquotient order.

(c) Figure out when two mm spaces  $X$  and  $Y$  are *comparable*, i.e., satisfy

$$X \triangleleft \lambda Y \quad \text{and} \quad Y \triangleleft \lambda X \quad (\triangleleft)_\lambda$$

for some  $\lambda \geq 1$ . Study the corresponding metric  $\text{dist}^{\triangleleft}(X, Y)$  defined as  $|\log \lambda|$  for the infimal  $\lambda$  in  $(\triangleleft)_\lambda$ .

(d) What can you say about  $X$  and  $Y$  if some  $\varepsilon$ -approximations to  $X$  and  $Y$  satisfy

$$X_\varepsilon \triangleleft Y_\varepsilon$$

for  $\square_1(X, X_\varepsilon) \leq \varepsilon$  and  $\square_1(Y, Y_\varepsilon) \leq \varepsilon$ ?

(e) Define  $X \triangleleft_\sigma Y$  if there is a subset  $X' \subset X$  with  $\mu(X \setminus X') \leq \sigma\mu(X)$  such that  $X' \triangleleft Y$ . Show that the Euclidean ball in  $\mathbb{R}^n$  of radius  $\sqrt{n}$  and the unit cube satisfy

$$[0, 1]^n \triangleleft B^n(\sqrt{n}) \triangleleft_\sigma C(\sigma)\sqrt{\log n}[0, 1]^n$$

for all  $\sigma < 1$ , where the ball and the two cubes (the unit and the scaled ones) are given their respective (nonnormalized) Lebesgue measures. (*Hint:* Use the lemma in 5.7 of [Mil–Sch].)

**Question.** Can one improve upon this  $\sqrt{\log n}$ ?

(f) Let  $A \subset \mathbb{R}^n$  be an arbitrary (centrally symmetric?) convex body. Does there exist an affine image  $A'$  of  $A$  such that

$$\lambda_\sigma^{-1} A' \triangleleft_\sigma B^n \triangleleft_\sigma \lambda_\sigma A',$$

where  $B^n$  is the Euclidean ball and  $\lambda_\sigma$  is of the order  $\log n$ ?

**Remark:** A more traditional (also open) problem (communicated to me by V. Milman) is to find  $A'$  with

$$\mu((\lambda_\sigma^{-1} A') \cap B^n) \geq \lambda_\sigma^{-1} \sigma \mu(A')$$

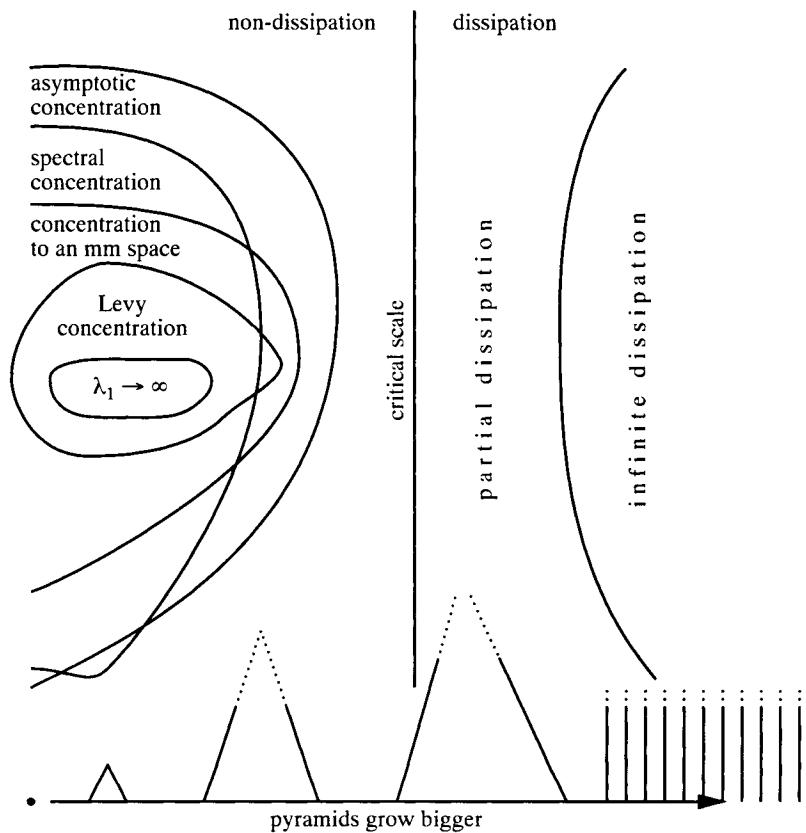
and

$$\mu(B^n \cap \lambda_0 A') \geq \sigma \mu(B^n)$$

with small  $\lambda_\sigma$  (say of order  $\log n$ ).

**3½.60. A schematic picture of concentration and dissipation.** One can think of concentrated (sequences of) mm spaces as those having small (weak limit) pyramids (where one can also use the pyramids for the sub-quotient order), while dissipation corresponds to large pyramids. An overall picture is on the next page

**3½.61. Concentration and dissipation for non-Lipschitz functions.** One can generalize the above setting by considering, instead of a metric, another structure on a measure space  $X$ . What is essential is a distinguished class of observables, i.e.,  $\mathbb{R}$ -valued (or more generally  $\mathbb{R}^n$ -valued) functions on  $X$  replacing our 1-Lipschitz functions. Notice that one can often think of such a class as a subsets of the set of all 1-Lipschitz functions on  $X$  for a suitable metric on  $X$ , e.g., the *maximal metric* for which all functions in our class are 1-Lipschitz. But it may happen that the distinguished functions are more concentrated than more general 1-Lipschitz functions.



**Examples:** (a) The classical case is that of  $\mathbb{R}^n$  with the product measure  $\mu_n = \mu \times \mu \times \dots \times \mu$  for some probability measure  $\mu$  on  $\mathbb{R}$ , where one is interested in the rate of concentration of the sum

$$\sigma_n: x = (x_1, \dots, x_n) \mapsto x_1 + x_2 + \dots + x_n \in \mathbb{R}$$

for  $n \rightarrow \infty$ . The law of large numbers asserts the concentration of  $\sigma_n(x)/n$  to its mean value, provided that  $\int_{\mathbb{R}} x d\mu_x < \infty$ , and the central limit theorem implies the concentration for  $\lambda_n \sigma_n(x)$  whenever  $\lambda_n/\sqrt{n} \rightarrow 0$ , and, say,  $\mu$  has compact support. Yet, we know that more general Lipschitz functions do not always concentrate in this way, e.g., on  $\{0, 1\}^n$ .

(b) The above generalizes to a measure space  $X$  with a given measurable automorphism (or endomorphism)  $A: X \rightarrow X$  and a function  $f: X \rightarrow \mathbb{R}$ . Here, one considers the pushforward measures  $\mu_n$  on  $\mathbb{R}^n$  given by  $n$ -tuples of functions

$$(f, f_1, \dots, f_{n-1}): X^n \rightarrow \mathbb{R},$$

where  $f_0 = f$  and  $f_i = f_{i-1} \circ A$ . The ergodic theorem asserts the concentration of  $\sigma_n(x)/n$  as  $n \rightarrow \infty$ , provided that  $A$  is ergodic and  $f$  is  $L_1$ , while more general Lipschitz functions on  $(\mathbb{R}^n, \mu_n)$  may be rather dissipating. (This happens, for example, if  $A$  is an irrational rotation on the circle, and  $f$  is a smooth function, e.g., an eigenfunction for the rotation, i.e.,  $f(z) = z^n$ .)

**Problems:** Study the (metric) geometry of  $(\mathbb{R}^n, \mu_n)$  for  $\mu_n$  above for “interesting” pairs  $(A, f)$ .

(c) Let  $\mu_n$  be some measure on  $\mathbb{R}^n$ , and let the admissible observables be normal projections to linear subspaces in  $\mathbb{R}^n$ . A specific example is provided by taking  $\mu_n$  equal to the normalized Lebesgue measure on some domain  $\Omega = \Omega_n \subset \mathbb{R}^n$ . Here, the classical Brunn–Minkowski theorem yields a nontrivial concentration for *convex* domains  $\Omega$ . Namely, if the principal curvatures  $0 \leq \kappa_1 \leq \kappa_2 \leq \dots \leq \kappa_{n-1}$  at every point in the boundary  $\partial\Omega$  of  $\Omega$  satisfy  $\kappa_1 \geq \varepsilon_n$ , where  $\varepsilon_n \sqrt{n} \rightarrow \infty$  as  $n \rightarrow \infty$ , then (the pushforwards of  $\mu_n$  under) the projections  $\mathbb{R}^n \rightarrow \mathbb{R}^m$  concentrate to point for every fixed  $p$  and  $n \rightarrow \infty$ . In fact, this remains true for arbitrary 1-Lipschitz maps  $\mathbb{R}^n \rightarrow \mathbb{R}^m$  as follows from Levy’s theorem. But, the Brunn–Minkowski result also applies to nonstrictly convex domains  $\Omega$  and partially log-convex measures in these, which gives us a concentration of projections  $\Omega \rightarrow \mathbb{R}^m$  to  $k$ -dimensional subsets in  $\mathbb{R}^m$  with  $k$  independent of  $m$ .

**Questions:** Let  $f_n : \Omega_n \rightarrow \mathbb{R}^m$  be arbitrary 1-Lipschitz functions. Do the pushforward measures  $\mu_n$  concentrate near  $k$  dimensional subsets in  $\mathbb{R}^m$  if we assume that  $\kappa_{k+1} \geq \kappa > 0$ ? Here we expect that every asymptotic subsequence  $\Omega_{n_i}$  concentrates to an mm space of dimension  $\leq q$ . More generally, we ask if this also happens to Riemannian manifolds  $X$  with  $\text{Ricci} \geq 0$ , where  $\text{Ricci} \geq \kappa > 0$  normally to subspaces of dimension  $\leq q$  in all tangent spaces  $T_x(X)$  (compare 3½.27(k)).

**3½.62. Concentration and dissipation of products and towers of fibrations.** We are concerned here with products  $F_1 \times \dots \times F_i \times \dots \times F_n$  for large  $n \rightarrow \infty$ , and so it matters how we define the product metric. In Riemannian geometry, one uses the pythagorean (or Euclidean)  *$\ell_2$  product*,  $\text{dist}_{\ell_2} = \sqrt{\sum_i \text{dist}_i^2}$ . More generally, one can use the  $\ell_p$ -product,  $\text{dist}_{\ell_p} = (\sum_i \text{dist}_i^p)^{1/p}$  for all  $p \in [0, \infty]$ , where the  $\ell_\infty$ -metric is just the sup metric  $\text{dist}_{\ell_\infty} = \sup_i \text{dist}_i$ . This metric is the *minimal possible* on the product, such that the projections to the fibers  $F_1 \times \dots \times F_i \times \dots \times F_n \rightarrow F_i$  are 1-Lipschitz. The maximal natural metric is  $\text{dist}_{\ell_1}$ . It is maximal among the metrics for

which all fiber embeddings  $F_i \rightarrow f_1 \times \cdots \times F_i \times \cdots \times f_n \subset F_1 \times \cdots \times F_i \times \cdots \times F_n$  are 1-Lipschitz.

As far as the measure is concerned, we assume here all  $\mu_i$  on  $F_i$  to be normalized, i.e.,  $\mu_i(F_i) = 1$ , and then our products are also normalized.

The problem which begs for resolution is that of the evaluation of basic (concentration) invariants of  $X^n = F_1 \times \cdots \times F_n$  in terms of suitable invariants of  $F_i$ . For example, we want to know when the  $X^n$  (and more generally the  $\lambda_n X^n$ ) concentrate or dissipate. We already know that the observable diameter of  $X^n$  is not determined by that of the factors  $F_i$ . For example, the observable diameter of the  $\ell_2$ -cartesian power  $[0, 1]^n$  is bounded as  $n \rightarrow \infty$ , while the vertex set of the cube  $[0, 1]^n$ , i.e., the cartesian power of  $\{0, 1\}$ , has  $\text{ObsDiam} \sim n^{1/4}$  (see 3 $\frac{1}{2}$ .42). Furthermore, it is clear that the powers  $\{0, 1\}^n$  dissipate even for the (smallest)  $\ell_\infty$ -metric, while the  $[0, 1]^n$  do not dissipate. In fact, if  $F$  is an arbitrary *disconnected* mm space, then the  $F^n = F \times F \times \cdots \times F$   $\varepsilon$ -dissipate for some  $\varepsilon > 0$ . This is obvious. What is more interesting is the following

**(1) Non-dissipation theorem:** *Let  $F$  be a compact, connected, and locally connected mm space (where we assume as usual that  $\text{Supp } \mu = F$ ). Then the  $\ell_\infty$ -powers  $F^n = (F \times \cdots \times F, \text{dist}_{\ell_\infty})$  do not dissipate as  $n \rightarrow \infty$ .*

**Proof.** We start with the following obvious

**Majorization lemma:** *Let  $F_0 \rightarrow F$  be a uniformly continuous map between mm spaces pushing forward the measure  $\mu_0$  of  $F_0$  to  $\mu$  on  $F$ . If the  $\ell_\infty$ -powers  $F_0^n$  do not dissipate as  $n \rightarrow \infty$ , then the  $F^n$  do not dissipate either.*

Next, we observe that our (compact, connected, locally connected)  $F$  can be majorized by the segment  $[0, 1]$ , i.e., it admits (as every child knows) a continuous (and hence uniformly continuous) map  $[0, 1] \rightarrow F$  pushing forward the Lebesgue measure to our  $\mu$  on  $F$ .

Finally, we recall (and this is the only nontrivial point) that the cubes  $[0, 1]^n$  do not dissipate as  $n \rightarrow \infty$ , even when we use the  $\ell_2$ -metric, which is much greater than  $\ell_\infty$  (see 3 $\frac{1}{2}$ .42), and the theorem follows.

**Remarks:** (a) The proof above looks like a cheat. Well, sometimes crime pays... (and an honest approach, harder but having the advantage of illuminating noncompact and nonlocally connected spaces, will not be pursued in this book).

(b) The majorization lemma indicates the usefulness of the order between

mm spaces coming from uniformly continuous, measure preserving maps  $f : X \rightarrow Y$ . Since we are interested in sequences of spaces, we must fix some modulus of continuity  $\delta(\varepsilon)$  and then stick to  $\delta(\varepsilon)$ -continuous maps. Of course, if  $X \rightarrow Y$  and  $Y \rightarrow Z$  are  $\delta(\varepsilon)$ -continuous, then their composition  $X \rightarrow Z$  need not be  $\delta(\varepsilon)$ -continuous, and so we do not get a true order relation for general  $\delta(\varepsilon)$  (it is necessary to have  $\delta(\varepsilon) \leq \varepsilon$ ). But, it still makes sense to speak of certain (quasi-)monotonicity of geometric invariants under the relation  $X \xrightarrow{\delta(\varepsilon)} Y$ . We suggest that the reader do that for the invariants we have met so far.

**(2) Concentration and random walks.** The isoperimetric profile of an mm space  $X$  is pretty well reflected in the behavior of the *random walk* on  $X$ . We study here only the case where  $X$  is a Riemannian manifold, so that the random walk amounts to the *heat flow*, i.e., the family of operators  $H(t) = \exp(t\Delta)$ , where  $\Delta$  is the positive Laplacian on  $X$ , i.e.,  $-\sum_i (\partial/\partial x_i^2)$ . This  $H(t)$  carries complete information about the spectrum  $\{\lambda_0, \lambda_1, \dots\}$  of  $\Delta$  for

$$\mathrm{Tr} H(t) = \sum_{i=0}^{\infty} \exp^{-\lambda_i t}.$$

Since  $\lambda_0 = 0$ , this trace  $\geq 1$  and if for some  $t_0 > 0$  we have  $\mathrm{Tr} H(t_0) \leq 1 + c_{t_0}$  with  $c_{t_0} < 1$ , we obtain a nontrivial lower bound on  $\lambda_1$ , namely

$$\lambda_1 \geq -(\log c_{t_0})/t_0. \quad (*)$$

In fact,

$$\lambda_1 = \lim_{t \rightarrow \infty} -(\log c_t)/t. \quad (*\infty)$$

On the other hand, this trace can be evaluated by the (*heat*) *kernel* of the operator  $H(t)$ , denoted by  $H(x, x'; t)$ , as

$$\mathrm{Tr} H(t) = \int_X H(x, x; t) dx.$$

This allows a bound on  $\mathrm{Tr} H(t)$  and hence on  $\lambda_1$  in terms of the  $L_\infty$ -bound on the heat kernel, i.e.,

$$\|H(t)\|_{L_\infty} \stackrel{\text{def}}{=} \sup_{x, x'} H(x, x'; t).$$

Notice at this point that  $H(x, x'; t)$  is a positive symmetric function on  $X \times X$  for each  $t > 0$  and  $\int_X H(x, x; t) dx = 1$  for all  $x$  and  $t$ . Also observe that the heat kernel of the scaled manifold  $sX = (X, s \mathrm{dist})$  equals

$$H_s(x, x'; t) = H(x, x'; s^{-2}t).$$

What is most important for us is the multiplicative property of the heat kernel for cartesian products  $Z = X \times Y$

$$H_Z((x, y), (x', y'); t) = H_X(x, x'; t)H_Y(y, y'; t).$$

This (trivially) implies, for example, the basic inequality

$$\lambda_1(X \times Y) = \min(\lambda_1(X), \lambda_1(Y))$$

used in 3 $\frac{1}{2}$ .42. And, we are about to prove a similar relation for *Riemannian fibrations*  $p: Z \rightarrow X$ . This means that  $Z$  is a Riemannian manifold with totally geodesic, mutually isometric fibers  $Y = Y_x = p^{-1}(x)$ , and (the differential of)  $p$  is isometric on the vectors normal to the fibers. Every such  $Z$  can be built out of a given  $X$  and  $Y$  by choosing a principal bundle over  $X$  with the group  $G = \text{Isom } Y$  and taking a connection in this bundle. Then one takes the associated bundle  $Z \rightarrow X$  with the  $Y$ -fibers and constructs in the obvious way a Riemannian metric on  $Z$  which turns  $Z$  into a Riemannian fibration such that the *horizontal* subbundle  $T^{hor}(Z) \subset T(Z)$  consisting of vectors normal to the fibers defines our connection.

The heat flow on such a  $Z$  is expressed by the famous *Kac- Feynmann formula*, which states that the heat flow on  $Z$  is obtained, roughly speaking, from that on  $X \times Y$  by an additional averaging along the fibers corresponding to the holonomy of the connection. This immediately leads to the following

**Kato inequality.**

$$\|H_Z(t)\|_{L_\infty} \leq \|H_X(t)\|_{L_\infty} \|H_Y(t)\|_{L_\infty} \quad (\times)$$

(as was explained to me by Jürg Frölich around 1980).

**Corollary:**

$$\lambda_1(Z) \geq \min(\lambda_1(X), \lambda_1(Y)) \quad (**)$$

**Proof.** To show this, we need the following modifications of  $(\infty)$  expressing the first eigenvalue  $\lambda_1$  of a Riemannian manifold  $X$  in terms of the heat decay  $d_t = \text{vol}^{-1}(X) - \|H_X(t)\|_{L_\infty}$ ,

$$\lambda_1 = \lim(-\log d_t)/t. \quad (+\infty)$$

Clearly,  $(\times)$  and  $(+\infty)$  imply the desired  $(**)$ , and so it only remains to prove  $(+\infty)$ . To do this, we expand the heat kernel into the Fourier series

$$H(x, x'; t) = \sum_{i=0}^{\infty} e^{-\lambda_i t} \varphi_i(x) \varphi_i(x') \quad (\star)$$

for the orthonormal eigenfunctions  $\varphi_i$  of  $\Delta$  on  $X$ , where we recall that  $\lambda_0 = 0$ , and  $\varphi_0$  is constant  $= (\text{vol}(X))^{1/2}$  (which makes  $\int_X \varphi_0^2 dx = 1$ ). The numbers  $\lambda_i$  grow, approximately, like  $i^{2/\dim(X)}$ , and the  $\varphi_i$  are smooth functions satisfying

$$\|\varphi_i\|_{L_\infty} = O(\lambda_i^{\dim(X)})$$

for large  $i \rightarrow \infty$ , as standard estimates show. Therefore,  $(\star)$  implies  $(+\infty)$ .

**Application:** Let  $\cdots \rightarrow X^n \rightarrow X^{n-1} \rightarrow \cdots \rightarrow X^0$  be a tower of Riemannian fibrations with fibers  $F_n$ ,  $n = 1, 2, \dots$ . If  $\lambda_1(F_n) \rightarrow \infty$ , then the sequence  $X^n$  asymptotically concentrates, and if  $\lambda_1(F_n) \geq \varepsilon > 0$ , then the  $X^n$  do not dissipate, provided that each  $X^n$  is assigned the normalized Riemannian measure.

**Example.** The above can be applied to towers of spherical fibrations, i.e., to the iterated unit tangent bundles of a unit sphere  $S^p$ , where

$$X_0 = S^p, \quad X_1 = T_1(S^p), \quad X_2 = T_1(X^1) \quad \cdots,$$

where each  $T_1(X)$  comes along with the Levi–Civita connection of  $X$ .

**Question.** What is the actual asymptotic behavior of  $\lambda_i(X^n)$  for these  $X^n$  as  $n \rightarrow \infty$ ?

Notice that the Kac–Feynmann formula suggests a sharpening of  $(**)$  of the form

$$\lambda_1(Z) \geq \min(\lambda_1(X), \lambda_1(Y) + \varepsilon),$$

where  $\varepsilon \geq 0$  is estimated from below in terms of the holonomy of the fibration  $Z \rightarrow X$ . For example, let  $Z_j$  be circle fibrations over a fixed base  $X$  with curvature forms  $i\omega$  for a given generic 2-form  $\lambda$  on  $X$ . Then an easy argument shows that  $\varepsilon \rightarrow \infty$  as  $j \rightarrow \infty$ , and hence  $\lambda_1(Z) \rightarrow \lambda_1(X)$ , provided that  $\dim X \geq 2$ . In fact, the growth of the curvature forces  $\|\varphi\|_{L_2}/\|\text{grad } \varphi\|_{L_2} \rightarrow 0$  for all functions  $\varphi$  having zero integrals around the fibers, which are themselves circles in this case. For general Riemannian fibrations  $Z \rightarrow X$ , one defines the space  $\Phi$  of functions on  $Z$  which are constant on the orbits of the isometry group  $\text{Isom } Y_x$  on each fiber  $Y_x$ ,  $x \in X$  (which are all mutually isometric), and the above applies to functions  $\varphi$  orthogonal to  $\Phi$  under suitable assumptions of “generic growth” of the curvature of the fibration.

**(2')** Everything we said automatically extends to  $X$ ’s with Riemannian metrics and to arbitrary (possibly non-Riemannian) measures (compare

[Gro]SGSS), where a basic example is  $X = \mathbb{R}$  with some measure  $\mu = \varphi(x) dx$ . Such an  $X = \mathbb{R}$  has  $\lambda_1 > 0$ , provided that

$$\min(\mu(-\infty, x], \mu(x, \infty]) \leq \text{const } \varphi(x)$$

for all  $x \in \mathbb{R}$  and some  $\text{const} \geq 0$ , as follows from the (trivial special case of the) celebrated inequality by Jeff Cheeger (see [Gro]SGSS). For instance, this is satisfied by  $\varphi(x) = e^{-|x|^p}$  for  $p \geq 1$ . Consequently,

*the Euclidean space  $\mathbb{R}^n$  with the measure  $\exp(-\sum_{i=1}^n |x_i|^p) dx$  has  $\lambda_1 \geq \varepsilon > 0$  independently of  $n$  (and  $p$ ).*

This, as was pointed out to me by G. Schechtman, applies to an evaluation of the observable diameters of  $\ell_p$ -balls in  $\mathbb{R}^n$  (see (5) below).

**(3)  $\ell_1$ -products, martingales, and  $\text{Ex}_\beta$ .** We shall indicate here an elementary approach to finding a bound on  $\text{ObsDiam } X^n$  for  $X^n = X \times X \times \cdots \times X$  ( $n$  factors) equipped with the  $\ell_1$ -product metric. In particular, we shall see that

$$\text{ObsDiam } X^n = O(\sqrt{n}),$$

as  $n \rightarrow \infty$ , provided that  $\text{diam } X < \infty$ , which is not bad since the ordinary diameter, as well as the characteristic size of this  $X^n$ , are  $\approx n$ . Also, we shall see that  $X^n$  with the  $\ell_p$ -product metric has  $\text{ObsDiam} = O(n^{1/2p})$  (compare for  $p = 2$ ), while the diameter and the characteristic size of these  $X^n$  are  $\approx n^{1/p}$ .

We use in our evaluation of  $\text{ObsDiam } X^n$  the classical idea of the Laplace–Gibbs transform of the measure  $f_*\mu$  on  $\mathbb{R}$  and set

$$\text{Ex}_\beta \stackrel{\text{def}}{=} \sup_f \int_X e^{\beta f(x)} d\mu_x,$$

where the  $f$  runs over all 1-Lipschitz functions with  $\int_X f(x) d\mu_x = 0$ . This  $\text{Ex}_\beta$  carries essentially the same information as the observable diameter or rather the central observable radius, but it is more suitable for the study of product spaces. Namely, *the  $\ell_1$ -product of two mm spaces with normalized measures satisfy*

$$\text{Ex}_\beta(X \times Y) \leq \text{Ex}_\beta(X) \text{Ex}_\beta(Y) \quad (\times \times)$$

**Proof.** Take a function  $f = f(x, y)$  on  $X \times Y$  and let  $\bar{f} = \bar{f}(x)$  be the function obtained by averaging  $f$  over the fibers  $Y = x \times Y \subset X \times Y$ , i.e.,

$$\bar{f} = \int_Y f(x, y) d\mu_y,$$

where we note that

$$\int_X \bar{f}(x) d\mu_x = \int_X \int_Y f(x, y) d\mu_x d\mu_y.$$

Write  $f(x, y) = \bar{f}(x) + g(x, y)$  for  $g \stackrel{\text{def}}{=} f - \bar{f}$  and observe that  $g$  has zero integral over all fibers  $x \times Y$ . Thus,

$$\int_X \int_Y e^{\beta f} = \int_X d\mu_x \int_Y e^{\mu \bar{f}(x)} e^{\beta g(x, y)} d\mu_y \leq \int_X e^{\beta \bar{f}(x)} \text{Ex}_\beta Y,$$

provided that  $f$ , and hence  $g$ , are 1-Lipschitz in the  $y$ -variable. Next, assuming that  $f$  is 1-Lipschitz in  $x$ , we observe that  $\bar{f}$  is Lipschitz as well, and consequently,

$$\left( \int_X e^{\beta \bar{f}(x)} \right) \text{Ex}_\beta(Y) \leq (\text{Ex}_\beta X)(\text{Ex}_\beta Y),$$

provided that  $\iint f(x, y) = \int \bar{f}(x) = 0$ .

**Corollary:** *The  $\ell_1$ -cartesian power  $X^n$  of  $X$  satisfies*

$$\text{Ex}_\beta X^n \leq (\text{Ex}_\beta X)^n \quad (\times^n)$$

for all  $\beta \in \mathbb{R}$ .

Now, in order to evaluate  $\text{ObsDiam } X^n$ , we must choose a suitable  $\beta$ , and we try  $\beta = \pm 1/\sqrt{n}$ . If  $\text{diam}(X) = d$ , then every 1-Lipschitz function  $f$  on  $X$  with zero mean is bounded by  $d$ , and

$$\int_X e^{\beta f} = \int_X 1 + \beta f + \frac{1}{2}\beta^2 f^2 + O(\beta^3 f^3)$$

for small  $\beta$ , and since we assume  $\int_X f = 0$ , we get

$$\int_X e^{\pm f/\sqrt{n}} = 1 + \frac{d^2}{2n} + O(n^{-3/2}).$$

It follows that

$$\text{Ex}_{\pm 1/\sqrt{n}}(X^n) \approx \left( 1 + \frac{d^2}{2n} \right)^n = \delta \approx e^{d^2/2}.$$

This trivially implies that

$$\text{ObsCRad}(X^n, -\kappa) = O(\sqrt{n}(\log \delta - \log \kappa)),$$

since

$$\int e^{\beta f} \geq \kappa_+ e^{\beta R}$$

for  $\beta \geq 0$  and  $\kappa_+ = \mu\{x \in X : f(x) \geq R\}$ , as well as

$$\int e^{\beta f} \geq \kappa_- \operatorname{Ex} \beta R$$

for  $\beta \leq 0$  and  $\kappa_- = \mu\{x \in X : f(x) \leq -R\}$ .

**Remark:** The above generalizes in an obvious way to towers of fibrations  $\rightarrow X^n \rightarrow X^{n-1} \rightarrow \dots \rightarrow X_0$ , where the sequence of functions  $\bar{f}_i$  on  $X$  for a given  $f = \bar{f}_n$  on  $X_n$  is defined with the partition of  $X^{i+1}$  into the fibers of the map  $X^{i+1} \rightarrow X^i$  as follows. We assume that these maps are measure-preserving for all  $i = 0, 1, \dots, n-1$ , and we recall the canonical probability (i.e., normalized) measures in the fibers. Then the function  $\bar{f}_{n-1}$  is defined by averaging  $f = \bar{f}_n$  along the fibers of  $X^n \rightarrow X^{n-1}$ , where we doublethink of this  $\bar{f} = \bar{f}_{n-1}$  as a function on  $X^{n-1}$  as well as on the original space  $X^n$  where it comes from  $X^{n-1}$  by composing with the projection  $X^n \rightarrow X^{n-1}$ . Then we do the same to  $\bar{f}^{n-1}$  on  $X^{n-1}$  and get  $\bar{f}^{n-2}$  on  $X^{n-2}$ , which is also thought of as the function on  $X^n$  constant on the fibers of the composed projection  $X^n \rightarrow X^{n-2}$ . Eventually, we obtain the sequence  $\bar{f}^n, \bar{f}^{n-1}, \dots, \bar{f}^0$ , where  $\bar{f}^i$  on  $X^n$  is constant on the fibers of  $X^n \rightarrow X^i$ , and so can be thought of as a function on  $X^i$ . This sequence is called a *martingale* associated to the partitions of  $X^n$  into smaller and smaller fibers of the projection  $X^n \rightarrow X^i$  as  $i$  runs through  $n, n-1, \dots$ .

All we need to make the argument work is the preservation of the 1-Lipschitz property under the averaging of functions  $f$  on  $X^{i+1}$  along the fibers of  $X^{i+1} \rightarrow X^i$ . This can be expressed in terms of our Lid-metric. We suggest that the reader work out the details and consult §7 in [Mil-Sch] for basic information and applications of martingales to the concentration problem.

Now we derive from the bound on  $\operatorname{ObsDiam} X^n$  for the  $\ell_1$  cartesian power the corresponding inequality for the  $\ell_p$ -product. To do this, we observe that our  $\ell_1$ -bound

$$\operatorname{ObsDiam} X^n = O(\sqrt{n})$$

is uniform for all spaces  $X$  with  $\operatorname{diam} X \leq 1$ . In particular, it holds true with the same implied constants for the space  $X_k$  consisting of  $k$  atoms of weight  $1/k$  with unit mutual distances. Then the  $\ell_p$ -metric on the cartesian power  $X_k^n$  obviously satisfies

$$\operatorname{dist}_{\ell_p} = (\operatorname{dist}_{\ell_1})^{1/p},$$

and every 1-Lipschitz function  $f$  on  $(X_k^n, \text{dist}_{\ell_1})$  is  $n^{1/p}$ -Lipschitz for the  $\ell_p$ -distance on  $X_k^n$ . Conversely, let  $f$  be 1-Lipschitz on  $(X_k^n, \ell_p)$ . We restrict  $f$  to a maximal  $\delta$ -separated net  $Y_\delta \subset X_k^n$ ,  $\delta = n^{1/2p}$  and observe that  $f$  is  $\lambda$ -Lipschitz on  $(Y_\delta|_{\text{dist}_{\ell_1}})$  for  $\lambda = \delta/\delta^p = n^{1/2p-1/2}$ . This  $f$  extends to a  $\lambda$  Lipschitz function  $f'$  on all  $(X_k^n, \ell_1)$ , where clearly  $\|f' - f\|_{L_\infty} \leq \lambda\delta^p + \delta = 2\delta$ . The function  $f'$  pushes the essential part of the measure of  $X_k^n$  to a segment in  $\mathbb{R}$  of length about  $\lambda\sqrt{n} \approx n^{1/2p}$ , since  $\text{ObsDiam}(X_k^n, \text{dist}_{\ell_1}) = O(\sqrt{n})$ . Hence

$$\text{ObsDiam}(X_k^n, \text{dist}_{\ell_p}) = O(n^{1/2p}). \quad (*)$$

Finally, we recall that the spaces  $X_k$  majorize, in the limit as  $k \rightarrow \infty$ , all spaces  $X$  with  $\text{diam } X \leq 1$ . This means that every such  $X$  appears as a  $\square_1$ -limit of some spaces  $Y_k \prec X_k$  as  $k \rightarrow \infty$ . This allows our extension of  $(*)$  to all spaces  $X$  with  $\text{diam } X \leq 1$ , since the bound  $(*)$  is uniform in  $k$ . Thus,

$$\text{ObsDiam}(X^k) = O(n^{1/2p}) \quad (\star)$$

for all  $p \geq 1$  and all spaces  $X$  with  $\text{diam } X < \infty$ . (We suggest that the reader quantify the argument and observe that everything is uniform in  $p \rightarrow \infty$ .)

**(4) Concentration of alternating functions on cartesian powers.** Whenever we have an mm space acted upon by a group  $G$ , we can ask for the concentration behavior of functions  $f$  on this space transformed by  $G$  according to a given representation of  $G$ . A particular example of interest is the power space  $X^n = X \times X \times \dots \times X$  acted upon by the permutation group  $S_n$ . Then one distinguishes two spaces of functions  $f$  on  $X^n$ : *symmetric* and *alternating*, where the former means invariance under  $S_n$ , i.e.,

$$f(x_1, \dots, x_i, x_{i+1}, \dots, x_n) = f(x_1, \dots, x_{i+1}, x_i, \dots, x_n),$$

and the latter signifies the change of sign under odd permutations

$$f(x_1, \dots, x_i, x_{i+1}, \dots, x_n) = -f(x_1, \dots, x_{i+1}, x_i, \dots, x_n).$$

The symmetric functions can be viewed as functions on the quotient space  $X/S_n$ , and the concentration properties of this space do not seem to be much better (at least to a casual eye) than those of  $X^n$  (but a significant difference may emerge under closer inspection, compare (5) below).

The alternating functions on  $X^n$  do not come from any (commutative, compare [Connes]) quotient of  $X^n$ , but they can be studied directly on  $X^n$  by looking, for example, at the *alternating spectrum* of  $X$  consisting of the eigenvalues of  $\Delta$  acting on the space of alternating functions. Every  $n$ -tuple

of pairwise nonequal eigenfunctions on  $X$ , say  $\varphi_{k_1}, \varphi_{k_2}, \dots, \varphi_{k_n}$  defines an alternating eigenfunction

$$\Phi = \Phi(x_1, \dots, x_n) = \det(\varphi_{k_i}(x_j))$$

on  $X^n$ , called an *orbital* in quantum mechanics, with the eigenvalue  $\lambda_{k_1} + \lambda_{k_2} + \dots + \lambda_{k_n}$ . The lowest orbital, made with the first eigenfunctions  $\varphi_0, \varphi_1, \dots, \varphi_{n-1}$  on  $X$ , gives us the lowest alternating eigenvalue of  $X^n$  by an elementary linear algebraic argument. Thus,

$$\lambda_1^{alt}(X^n) = \sum_{i=0}^n \lambda_i(X) \quad (*)$$

for all compact Riemannian manifolds  $X$ . It follows that  $\lambda_1^{alt}(X^n)$  is asymptotic to  $n^{1+2/d}$  for  $d = \dim X$ , and the (obviously defined) alternating observable diameter of  $X^n$  decays like  $n^{-1-2/d}$ . (This fast decay is closely related to the stability of matter, see [Lieb]).

**Problem:** Evaluate the alternating visual diameter for the  $\ell_p$ -power  $X^n$  of a given mm space  $X$ . Study in general the asymptotic geometry of  $X^n$  with the action of  $S_n$  taken into account. In particular, decide for which sequences of scaling numbers  $\rho_i$  the sequence  $\rho_i X^n$  concentrate or dissipate and what happens on the *critical scale* where  $\rho_i$  is asymptotic to  $(\text{ObsDiam}(X^n))^{-1}$  (with a given type of symmetry).

**(5) Euclidean geometry of simplices and  $\ell_p$ -balls.** Besides products, such as the cube  $[0, 1]^n$ , there are many other interesting spaces, e.g., polyhedra with  $S_n$  actions. The first among these is the Euclidean simplex

$$\Delta^n = \{x_0, \dots, x_n \geq 0 : \sum_{i=0}^n x_i = 1\},$$

where we start by observing that the distance function from a vertex gives us the measure  $\frac{x^n}{n!} dx$  on  $\mathbb{R}_+$  whose essential part spreads over the segment of length  $1/n$  around zero. Thus, the observable diameter of  $\Delta^n$  must be at least  $\text{const}/n$ . Next, we recall that the moment map  $\mathbb{C}\mathbb{P}^n \rightarrow \delta^n$  (see 3½) pushes the  $U(n+1)$ -invariant measure of  $\mathbb{C}\mathbb{P}^n$  forward to the Lebesgue measure on  $\Delta^n$ , and since this map is 1-Lipschitz, we have

$$\text{ObsDiam } \Delta^n \leq \text{ObsDiam } \mathbb{C}\mathbb{P}^n = O\left(\frac{1}{\sqrt{n}}\right).$$

In fact,

$$\text{ObsDiam } \Delta^n = O\left(\frac{1}{n}\right), \quad (\star)_\Delta$$

as follows from Schechtman's theorem (see below), but even the  $o(1/\sqrt{n})$ -concentration of the distance function on  $\Delta^n$  from the center is not totally obvious. This concentration can be expressed in terms of the volumes of the intersections of  $\Delta^n$  with the Euclidean  $R$ -balls in  $\mathbb{R}^{n+1} \supset \Delta^n$  with variable  $R$ , and then the relevant information about  $\Delta^n$  follows from the corresponding volume properties of intersections of the Euclidean and  $\ell_1$ -balls in  $\mathbb{R}^{n+1}$ . In fact, Schechtman and Schuckenschläger (see [Sch–Sch]) evaluated the intersections between  $\ell_p$ - and  $\ell_q$ -balls in  $\mathbb{R}^n$  for all  $p$  and  $q$  as follows.

Let  $B_p \subset \mathbb{R}^n$  denote the ball with respect to the  $\ell_p$ -metric of radius  $R_p$ , such that the Euclidean volume of  $B_p = 1$ . For example, if  $p = 2$ , this is the ordinary Euclidean ball of radius

$$(\Gamma(1 + n/2))^{1/n}/2\Gamma(3/2) \approx \sqrt{n}$$

and if  $p = 1$ , this is the polyhedron

$$B_1 = \{x_1, \dots, x_n : \sum_{i=1}^n |x_i| \leq \frac{(n!)^{1/n}}{2} \approx n\},$$

where the faces are the copies of  $\Delta^{n-1}$  scaled by  $\lambda_n \approx n$ . Then there is a critical constant  $C_{pq} > 1$  (explicitly computed in [Sch–Sch]) such that as  $n \rightarrow \infty$ ,  $\text{vol}(B_p^n \cap tB_q^n) \rightarrow 0$  for  $t < C_{pq}$  and  $\text{vol}(B_p^n \cap tB_q^n) \rightarrow 1$  for  $t > C_{pq}$ . We use this for  $p = 1$  and  $q = 2$  and conclude that the distance function  $x \mapsto \|x\|_{\ell_2}^2$  on the unit  $\ell_1$ -ball  $\{x_1, \dots, x_n : \sum_{i=1}^n |x_i| \leq 1\}$  has concentration  $o(1/\sqrt{n})$  for  $n \rightarrow \infty$ . This implies the similar concentration on the boundary  $\partial B_1^n(1)$  and hence on the simplex  $\Delta^{n-1}$ .

**Spectral evaluation of ObsDiam  $B_p^n(1)$ .** We recall that the (Lebesgue measure on) the  $\ell_p$  ball

$$B_p^n(n^{1/p}) = \{x_1, \dots, x_n : \sum |x_i|^p \leq n\}$$

is well-approximated by the (canonical) product measure  $\exp(\sum |x_i|^p) dx$  on  $\mathbb{R}^n$  (see 3½.25). Since this measure has  $\lambda_1 \geq \varepsilon > 0$ , it has  $\text{ObsDiam} = O(1)$  and thus we have a similar bound for the above balls. In fact, by rescaling these  $\ell_p$ -balls to unit size and then taking 3½.25 into account, we arrive at the following result (communicated to me by G. Schechtman)

$$\text{ObsDiam } B_p^n(1) = O(n^{-1/p}). \tag{★}_p$$

Notice that  $(★)_\Delta$  easily follows from  $(★)_1$ .

**Remarks and open problems:** (a) Probably the above argument can be adjusted for the evaluation of the spectral radii of the  $\ell_p$ -balls and that

of  $\Delta^n$ , as well as for the study of the alternating observable diameters of these spaces.

(b) There are many other interesting polyhedra with  $S_n$ -actions besides  $[0, 1]^n$ ,  $B_1^n(1)$ , and  $\Delta^n$ , where the problem of evaluating the observable diameter (with and/or without symmetries) begs for solution. An attractive case is that of the space of *bistochastic matrices*,

$$\{x_{ij} \geq 0 : \sum_{i=1}^n x_{ij} = 1 \text{ for } j = 1, \dots, n, \text{ and } \sum_{i=1}^n x_{ij} = 1 \text{ for } i = 1, \dots, n\}$$

and such generalizations as

$$\{x_{ijk} \geq 0 : \sum_i x_{ijk} = 1, \sum_j x_{ijk} = 1, \sum_k x_{ijk} = 1\}.$$

Furthermore, one can start with a given (convex) subset  $B \subset \mathbb{R}^m$  and make, for example,

$$B_n(R) = \{x_{ij} \in B : \sum_{i=1}^n x_{ij} = R = \sum_{j=1}^n x_{ij}\},$$

leading to the same spectrums of open problems (compare [Barv]).

(c) The canonical (and microcanonical) measures on  $\mathbb{R}^n$  arising in statistical mechanics provide us with an inexhaustible source of examples where we wish to evaluate our invariants for  $n \rightarrow \infty$ .

**3½.63. Fine geometry in  $\mathcal{X}$ .** Eventually, one wants to study the asymptotic mm geometry of particular (sequences of) spaces with much greater precision than provided by the metric and other structures on  $\mathcal{X}$ . The major examples are supplied by various *configuration spaces* coming from geometry, probability theory, statistical mechanics, and quantum field theory. A famous case is the *self-avoiding random walk* on the standard lattice  $\mathbb{Z}^2 \subset \mathbb{R}^2$ . Here, our  $X^n$  is the space of *injective* maps  $x$  from  $\{1, 2, \dots, n\}$  to  $\mathbb{Z}^n$  with  $\text{dist}(x(i), x(i+1)) = 1$  for  $i = 1, \dots, n-1$ . One gives equal measures to all atoms  $x$  constituting  $X^n$  (maybe one should introduce smart weights?) and wants to understand the asymptotic behavior of functions  $f(x)$  on  $X^n$  recording the geometry of a walk  $x : \{1, 2, \dots, n\} \rightarrow \mathbb{Z}^2$ , e.g., the diameter of its image. Amazingly, no *nontrivial rigorous* result seems to be available for these  $X^n$ .

What can the space  $\mathcal{X}$  offer us as a tool for approaching real, hard problems? As it stands, precious little. Actually, even rather crude invariants, such as the first eigenvalue  $\lambda_1(X)$  is *not* continuous on  $(\mathcal{X}, \square_1)$ ,

which shows how coarse the geometry of  $\mathcal{X}$  is. There are several avenues for improvement. For example, one can make  $\lambda_1$  more continuous on  $\mathcal{X}$  by using the following standard  $\varepsilon$ -regularization trick of setting

$$\lambda_1^\varepsilon(X) = \sup_{X'} \lambda_1(X'),$$

where  $X'$  runs over all mm spaces with  $\square_1(X, X') \leq \varepsilon$ . (We suggest that the reader think of what this trick does to the whole spectrum.) However, it seems unlikely that a truly deep asymptotic theory can be developed for all spaces in  $\mathcal{X}$ . Apparently, one should distinguish a certain class (or classes) or *regular* spaces  $X$  (as well as of regular observables  $f$  on these  $X$ ) and then introduce a fine “smooth” structure on the space  $\mathcal{X}_{\text{reg}} \subset \mathcal{X}$  of the regular  $X$ ’s. Here are some properties which make our mm space look regular.

1. All  $\lambda_i$  are defined and are bounded away from zero. If we deal with a sequence  $X^n$ , then the  $\lambda_i(X^n)$  must have “regular” asymptotics.
2. The ratios of measures of small balls of given radii in an individual  $X$  are bounded, and such balls, say  $B(R)$  and  $B(r)$  in  $X^n$ , have “regular asymptotics” for  $\mu(B_n(R))/\mu(B_n(r))$ , e.g., as  $(R/r)^{\alpha n}$  for  $n \rightarrow \infty$ .
3. The isoperimetric properties of  $X^n$  behave regularly for  $n \rightarrow \infty$ .
4. Regular observables  $f: X^n \rightarrow \mathbb{R}^k$  should not only concentrate, but the pushforward measures  $\underline{\mu}_n = f_*(\mu)$  on  $\mathbb{R}^k$  must have reasonable density functions  $s_n(y)$  (with respect to the Lebesgue measure on  $\mathbb{R}^k$ ), such that  $(1/n) \log s_n(y)$  would converge as  $n \rightarrow \infty$  to a nice (concave, piecewise analytic, etc.) function  $\sigma(y)$  on  $\mathbb{R}^k$ .

Additionally, the “fine structure” on  $\mathcal{X}_{\text{reg}}$  can be expressed, for example, by a metric which is (much) stronger than  $\square_1$ , but more likely it should be a more sophisticated infinitesimal structure reflecting particular types of asymptotics of  $X^n$  as those established (or at least expected) in statistical mechanics. We humbly hope that the general ambiance of  $\mathcal{X}$  can provide a friendly environment for treating asymptotics of many interesting spaces of configurations and maps.

# Chapter 4

## Loewner Rediscovered

### A. First, some history (in dimension 2)

In 1949, Loewner proved the following (unpublished, see [Pu] or the proofs in [Berger]<sub>Cours</sub>, [Berger]<sub>ombre</sub>, [Berger]<sub>LGRG</sub>):

**4.1. Theorem:** *Let  $(\mathbb{T}^2, g)$  be a 2-torus equipped with a Riemannian metric  $g$  and let  $l(g)$  be the infimum of the lengths of all closed curves in  $\mathbb{T}^2$  not homotopic to 0. Then  $\text{Area}(\mathbb{T}^2, g) \geq (\sqrt{3}/2)l^2(g)$ . Moreover, if  $\text{Area}(\mathbb{T}^2, g) = (\sqrt{3}/2)l^2(g)$ , then  $(\mathbb{T}^2, g)$  is necessarily the equilateral flat torus, i.e., defined by  $\mathbb{R}^2/\Lambda$ , where  $\Lambda$  is the lattice in  $\mathbb{R}^2$  generated by the vectors  $(0, 1)$  and  $(1/2, \sqrt{3}/2)$ .*

The proof of Loewner's theorem begins with an application of the fundamental theorem of conformal representation in order to write  $g = f \cdot g_0$ , where  $f$  is a function on  $\mathbb{T}^2$  and  $g_0$  is flat. Since  $g_0$  is flat, it has a transitive group  $G$  of isometries; an appropriate averaging of  $f$  by the action of  $G$  has the effect of decreasing area and increasing  $l$ . Since  $G$  is transitive, this averaging process yields a constant function, and one is reduced to the case of a flat torus, for which the result is simple (compare [Keen]).

In [Pu], P.M. Pu remarks that the Loewner method can be directly applied to the projective plane  $(\mathbb{RP}^2, g)$  to give (see [Berger]<sub>Cours</sub> or [Berger]<sub>LGRG</sub>, p. 303)

**4.2. Proposition:** *Given the projective plane  $\mathbb{RP}^2$  equipped with a Riemannian metric  $g$ , let  $l(g)$  denote the infimum of the lengths of closed curves not homotopic to zero. Then  $\text{Area}(\mathbb{RP}^2, g) \geq (2/\pi)l^2(g)$ , and if  $\text{Area}(\mathbb{RP}^2, g) = (2/\pi)l^2(g)$ , then  $g$  is necessarily the canonical metric on  $\mathbb{RP}^2$ .*

**4.3.** The Loewner technique does not apply to surfaces  $V$  of genus  $> 1$  (except asymptotically, see [Katok]), but by the method of harmonic forms and, independently, Accola and Blatter (see [Acc], [Blat]) we have

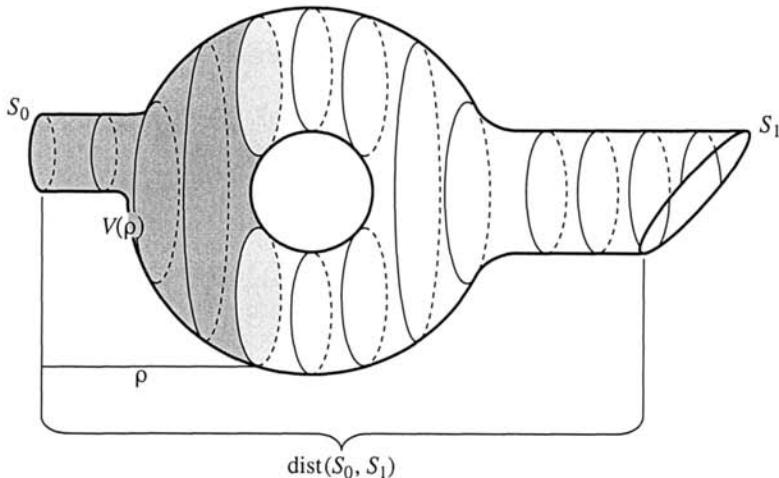
**4.4. Theorem:** *For each  $\gamma > 1$ , there is a constant  $C(\gamma) > 0$  such that  $\text{Area}(V, g) > C(\gamma)l^2(g)$  for any surface  $(V, g)$  of genus  $\gamma$ .*

**4.5<sub>+</sub>**. The constant  $C(\gamma)$  guaranteed by the method of Accola and Blatter is far from optimal. In fact, these authors rely on the embedding of a Riemann surface into its Jacobian (torus) and then apply the Minkowski theorem (see 4.31). This gives  $C(\gamma) \sim \gamma^{-1}$ , which tends to zero as  $\gamma \rightarrow \infty$ . On the other hand, one can get a universal constant independent of  $\gamma$  with the following

**4.5<sub>2+</sub><sup>1</sup>** **Besicovitch lemma (compare [Besi] and 4.28bis).** *Let  $V$  be a compact surface with two boundary components  $\partial V = S_0 \sqcup S_1$ , and let  $\ell$  denote the length of the shortest closed curve in  $V$  homologous to  $S_0$  (and hence to  $S_1$ ) with respect to a given Riemannian metric  $g$  on  $V$ . Then the area of  $(V, g)$  is bounded from below by*

$$\text{Area}(V, g) \geq \ell \text{dist}(S_0, S_1). \quad (*)$$

**Sketch of the proof.** Look at the levels  $S(r)$  of the distance function  $r(x) = \text{dist}(x, S_0)$  on  $V$ .



These start with  $S(0) = S_0$  and remain closed (possibly nonsmooth and disconnected) curves homologous to  $S_0$  for  $r \leq \text{dist}(S_0, S_1)$ . The classical

(and rather obvious) *coarea formula* says that the area  $a(\rho)$  of the region  $V(\rho) = \{x \in V : r(x) \leq \rho\}$  satisfies

$$a(\rho) = \int_0^\rho \text{length } S(r) dr,$$

and so

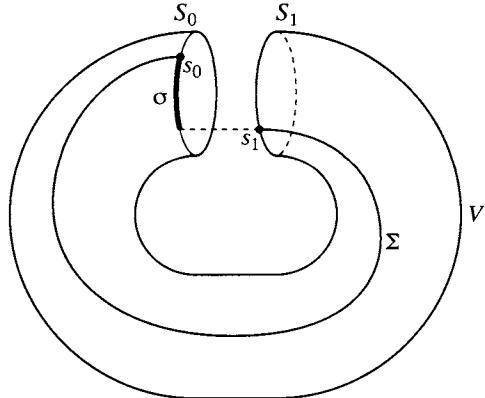
$$\text{Area}(V) \geq \text{Area } V(\rho) = a(\rho) \geq \ell\rho$$

for all  $\rho \leq \text{dist}(S_0, S_1)$ , which yields the lemma for  $\rho = \text{dist}(S_0, S_1)$ .

**4.5<sub>4+</sub><sup>3</sup>** **Corollary.** *Every closed, orientable surface  $V$  of genus  $\geq 1$  admits a closed curve of length  $\ell$  which is not null-homologous and satisfies*

$$\frac{1}{2}\ell^2 \leq \text{Area}(A). \quad (**)$$

**Proof.** Cut  $V$  along the *shortest* non-dividing (and hence not null-homologous) curve  $S$  and apply Besicovitch's lemma to the resulting surface  $V'$  with the two boundary components  $S_0$  and  $S_1$  corresponding to  $S$ .

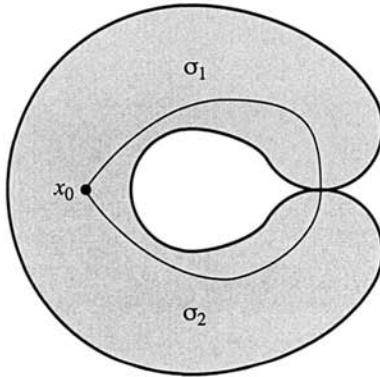


Then, according to (\*), there is a curve  $\Sigma$  in  $V'$  of length  $\delta \leq (\text{Area}(V'))/\ell$  joining two points  $s_0 \in S_0$  and  $s_1 \in S_1$ . This  $\Sigma$ , together with a segment  $\sigma \in S$  of length  $\leq \frac{1}{2} \text{length } S = \frac{1}{2}\ell$  make a closed curve in  $V$  which is not homologous to zero and has length  $\leq \delta + \ell/2$ , which cannot be shorter than  $\ell$ . Thus,  $\delta + \ell/2 \geq \ell$ , or  $\ell \leq 2\delta$ , and so

$$\text{Area}(V) = \text{Area}(V') \geq \ell\delta \geq \frac{1}{2}\ell^2.$$

This argument using the *coarea method* is more elementary than Loewner's *length-area* proof (as it is called by complex analysts), but it does not give us the sharp constant for the torus. Still, it seems to serve better than the Jacobian embedding of Accola–Blatter, at least for large genus  $\gamma$ . And yet, the Jacobian is vindicated by other geometric applications. For example, the very discrepancy between the Accola–Blatter  $C(\gamma) \sim \gamma^{-1}$  and the (asymptotically) optimal  $C_0(\gamma) \sim \gamma / (\log(\gamma))^2$  (see below) led Buser and Sarnak to a new approach to the *Schottky problem* on the characterization of Jacobi varieties of algebraic curves (see [Gro]SII and the references therein).

**4.6+** Should we be content with having improved  $C(\gamma) \sim \gamma^{-1}$  to  $C(\gamma) \geq 1/2$ ? To get a perspective, try surfaces  $V$  of genus  $\gamma \geq 2$  with a metric  $g$  of constant curvature  $-1$ . An obvious way (going back to Gauss and Minkowski) of finding a *noncontractible* loop in  $V$  based at a given point  $x_0 \in V$  is to consider the maximal simply connected open (or minimal non-simply connected closed) disk  $B(x_0, R)$  which meets itself at the boundary.



Then the loop  $S$  based at  $x_0$  and comprised of two geodesic segments  $\sigma_1$  and  $\sigma_2$  joining  $x_0$  with a meeting point at the boundary  $\partial B(x_0, R)$  has length  $\ell_0 = 2R$ . On the other hand,  $\text{Area } V \geq \text{Area } B(x_0, R) \simeq e^R$  for large  $R$ , say for  $R \geq 1$ . On the other hand, the area of this  $V = (V, g_0)$  is proportional to the Euler characteristic  $\chi(V) = 2(\gamma - 1)$ , i.e.,  $\text{Area}(V) = 4\pi(\gamma - 1)$ . Thus,  $\ell_0 \leq C \log(\gamma)$  and  $\text{Area}(V, g_0) \approx \gamma$ , which implies that

$$\text{Area}(V, g_0) \geq C_0(\gamma) \ell_0^2$$

for

$$C_0(\ell) \geq \text{const } \gamma / (\log \gamma)^2$$

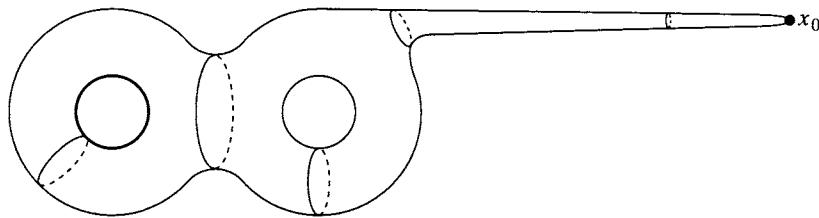
and some universal constant  $\text{const} > 0$ . This suggests that  $C(\gamma) \sim \gamma / (\log \gamma)^2$  for all metrics  $g$ . Indeed we have the following

**Theorem (see [Gro]SII).** *An arbitrary closed (possibly nonorientable) surface  $(V, g)$  admits a closed geodesic nonhomologous to zero mod 2 of length  $\ell$ , such that*

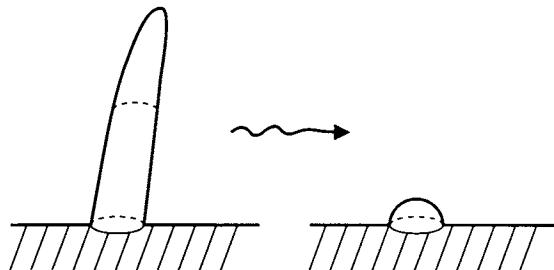
$$\text{Area}(V, g) \geq C(\gamma) \ell^2 \quad (*)$$

for  $C(\gamma) = \text{const} \gamma / (\log \gamma)^2$ , where  $\text{const} > 0$  is a universal constant.

**About the proof.** If we try to find a short loop  $S$  based at a given point  $x_0 \in V$ , then we run into trouble if  $x_0$  lies at the tip of a long narrow finger.



So, we must avoid such  $x_0$  and look for  $S$  somewhere else. In fact, we can cut away such long fingers and replace them with hemispherical caps.



This does not shorten the length of the minimal curves nonhomologous (and/or nonhomotopic) to zero and diminishes the area of  $V$  at the same time. So, we may reduce the general case to a “fingerless” one where the balls  $B(R) \subset V$  harboring no loops which do not contract in  $M$ , satisfy

$$\text{Area } B(R) \geq R^2. \quad (+)$$

This, combined with the above argument employed for the metric  $g_0$  of constant curvature, yields a noncontractible curve of length  $\ell \leq 2\sqrt{\text{Area}(V, g)}$

which is actually slightly worse than the above (\*\*). However, if we fully exploit the inequality (+) for *all* balls in  $V$ , and not just for a single  $B(R) = B(x_0, R)$ , then we can do much better by relating the area of  $V$  (satisfying (+)) to the *simplicial volume* of  $V$  (see Ch. 5.F<sub>+</sub>) which happens to be equal to  $-c_0\chi(V)$  for surfaces  $V$ . (See [Gro]<sub>FRM</sub> and [Gro]<sub>SII</sub> for the actual proof).

**4.7+** It is not at all obvious what the extremal metrics  $g$  on surfaces of genus  $\gamma$  with the *maximal* ratio  $\text{Area}(V, g)/\ell^2(g)$  should be. They are definitely *not* of constant curvature for  $\gamma \geq 2$ . See [Cal] for some information about these  $g_{\text{extreme}}$ .

## B. Next, some questions in dimensions $\geq 3$

**4.8.** As a reference for the discussion in this section, the reader may consult [Berger]<sub>GR</sub> and [Berger]<sub>Pu</sub>. We now consider the case of manifolds of dimension  $\geq 3$ . In [Pu], Pu notes that the Loewner technique applies to conformal Riemannian structure to homogeneous Riemannian structures; unfortunately, the space of conformal classes of Riemannian structures in dimension 3 is infinite-dimensional and thus any inequality similar to that of Loewner's theorem for a single conformal class is of limited interest.

**4.9.** Note that if  $(V, g)$  is a Riemannian  $n$ -manifold and if we continue to denote by  $\nu(g)$  its volume and  $l(g)$  the infimum of the lengths of closed curves not homotopic to zero, then it is futile to hope for the existence of a constant  $C(V) > 0$  such that  $\nu(g) \geq C(V)l^n(g)$  for any nonsimply connected  $V$ . For example, if  $W$  is simply connected, then the ratio  $\nu(g)/l^n(g)$  can be made arbitrarily small for the manifold  $S^1 \times W$  equipped with the product metric.

In order for  $C(V)$  to be positive, it appears to be necessary, as in the case of  $\mathbb{T}^2$  or  $\mathbb{RP}^2$ , that the degree-1 homology generate all of the topology of  $V$ , or at very least the fundamental class of  $V$ . The likely candidates for such a theorem might therefore pertain to  $\mathbb{T}^n$  and  $\mathbb{RP}^n$ . Thus,

**4.10. Question:** Does there exist a constant  $C_{\mathbb{T}}(n) > 0$  such that  $\nu(g) \geq C_{\mathbb{T}}(n)l^n(g)$  for every Riemannian metric  $g$  on  $\mathbb{T}^n$ ? If so, does equality characterize the flat tori for which the ratio is minimal? (For the corresponding, often nonunique lattices, called critical lattices, see [Cass], p. 141, and [Klin], p. 133). The same question (cf. 4.7) can be posed with  $\nu(g) \geq C(n)l_1(g) \cdots l_n(g)$ .

**4.11. Question:** *The same question as in 4.10 can also be posed with  $C_P(n)$  for  $\mathbb{R}\mathbb{P}^n$ , with equality implying that  $(\mathbb{R}\mathbb{P}^n, g)$  is isometric to  $\mathbb{R}\mathbb{P}^n$  with its canonical metric.*

**4.12.** Next, we can pose the following generalization of Question 4.11: Let  $K\mathbb{P}^n$  denote the projective space of  $k$ -dimension  $n$  over the field  $K$  equal to  $\mathbb{C}$  if  $k = 2$ ,  $\mathbb{H}$  if  $k = 4$ , and  $\mathbf{Ca}$  if  $k = 8$  (so that necessarily  $n = 2$ ). The real dimension is then  $kn$ . Given a Riemannian structure  $g$  on  $K\mathbb{P}^n$ , we denote by  $\nu(g)$  its volume and by  $m(g)$  the infimum of the volumes of  $k$ -dimensional submanifolds of  $K\mathbb{P}^n$  that are homologous to the (canonically embedded) projective line  $K\mathbb{P}^1$ .

**4.13. Question:** *Is there a constant  $C(n, k) > 0$  such that for every metric  $g$  on  $K\mathbb{P}^n$ , we have  $\nu(g) \geq C(n, k)m^n(g)$ ? What does equality imply?*

To conclude, consider the product  $V = V_1 \times V_2$  of two compact manifolds. Given a Riemannian structure on  $V$ , let  $\nu_i(g)$  denote the infimum of the volumes of submanifolds of dimension  $n_i = \dim(V_i)$  and homologous to  $V_i$ .

**4.14. Question:** *Under what conditions on the  $V_i$  does there exist a constant  $C(V_1, V_2)$  such that*

$$\nu(g) \geq C(V_1, V_2)\nu_1(g)\nu_2(g)$$

*for every  $g$  on  $V_1 \times V_2$ ? What does equality imply?*

We note that if  $V_1 = V_2 = S^1$  (cf. 4.7), or, more generally, if each  $V_i$  is a torus, then a more subtle definition of the  $\nu_i(g)$  is needed in order for such a constant to exist.

In the following section, we will provide answers to most of these questions.

## C. Norms on homology and Jacobi varieties

**4.15. Norms on the homology groups of a Riemannian manifold.** Recall that a *singular integral Lipschitz chain* (resp. *real chain*) of dimension  $p$  in a Riemannian manifold  $V$  is a formal sum of the form  $a = \sum_i \lambda_i c_i$ , where the  $\lambda_i$  are integers (resp. real numbers) and the  $c_i$  are Lipschitz mappings of the standard  $p$ -simplex into  $V$ . The *mass* of a Lipschitz 1-chain  $a$  is defined as the number  $M(a) = \sum_i |\lambda_i| \text{length}(c_i)$ . Evidently,  $M(a) = \sup |\int_a \omega|$ , where  $\omega$  ranges over all differential 1-forms for which  $\sup_{v \in V} |\omega(v)| \leq 1$  where  $|\cdot|$  is the Euclidean norm on  $T_v^*V$ .

In order to equip the space of  $p$ -chains with a norm that has the same additivity property and that is dual to a sup-like norm on the space of  $p$ -forms, we proceed as follows (cf. [Laws], p. 51, and [Fed]GMT).

Given a Euclidean space  $E$ , we denote its norm and the induced norms on the exterior powers  $\Lambda^p E$  by  $|\cdot|$ . The *mass* norm on  $\Lambda^p E$  is then defined by

$$\|e\| = \inf \left\{ \sum_i |e_i| : e = \sum_i e_i, \text{ each } e_i \text{ nondecomposable} \right\},$$

and, on  $\Lambda^p E^*$ , we define the *comass* as

$$\|\varphi\|^* = \sup\{|\varphi(e)| : e \in \Lambda^p E \text{ and } \|e\| \leq 1\}.$$

The *comass* of a differential form  $\omega$  is by definition

#### 4.16.

$$M^*(\omega) = \sup |\omega(\tau_1, \dots, \tau_p)|,$$

where the sup ranges over the orthonormal frames in  $T(V)$ . The mass of a chain is the dual norm,

#### 4.17.

$$M(a) = \sup \left\{ \left| \int_a \omega \right| : \omega \text{ is a differential form with } M^*(\omega) \leq 1 \right\}.$$

These definitions imply that  $M(\sum_i \lambda_i c_i) = \sum_i |\lambda_i| \text{vol}(c_i)$ . For example, in  $\mathbb{C}\mathbb{P}^2$  equipped with its standard metric, as well as in every Kähler manifold, the comass of the Kähler form  $\omega$  is 1, as follows from Wirtinger's inequality (see 6.35).

We now equip  $H_p(V; \mathbb{Z})$  and  $H_p(V; \mathbb{R})$  with quotient norms by defining  $\|\alpha\| = \inf\{M(a) : a \in \alpha\}$  for any integer or real class  $\alpha$ . By 5.1.6 of [Fed]GMT (or [Fed–Flem], 9.6, completed by [Fed]VP, §3 for the real case), these are indeed norms. Let  $\alpha$  denote an integer class and  $\alpha_{\mathbb{R}}$  the real class that it determines. Since  $\alpha \in \alpha_{\mathbb{R}}$ , we have  $\|\alpha\| \geq \|\alpha_{\mathbb{R}}\|$ , and the following theorem shows that the norm  $\alpha \mapsto \|\alpha_{\mathbb{R}}\|$  on  $H_p(V; \mathbb{Z})$  plays the same role as the limit norm on the homotopy groups introduced in Proposition 2.22.

**4.18. Theorem** (cf. [Fed]VP §5): *For each class  $\alpha \in H_p(V; \mathbb{Z})$ ,*

$$\lim_{m \rightarrow \infty} \frac{\|m\alpha\|}{m} = \|\alpha_{\mathbb{R}}\|.$$

**Remark:** Examples are known for which  $\|\alpha\| > \|\alpha_{\mathbb{R}}\|$  and even for which  $(1/m)\|m\alpha\| > \|\alpha_{\mathbb{R}}\|$  for all  $m$ . This phenomenon has been described by

F. Almgren (cf. [Fed]VP, p. 397) in the case of a degree-1 class in an oriented 3-manifold. In [Laws], there are also striking examples of flat tori and a systematic study of the norms  $\|\alpha\|$  and  $\|\alpha_{\mathbb{R}}\|$  (see [Fed]VP, p. 394, and section 4.33 below).

**4.19. Definition:** The norm  $\alpha \mapsto \|\alpha_{\mathbb{R}}\|$  on  $H_p(V; \mathbb{Z})$  is called the *stable norm*. An integral class  $\alpha$  is called *stable* if there exists an integer  $m$  such that  $(1/m)\|m\alpha\| = \|\alpha_{\mathbb{R}}\|$ .

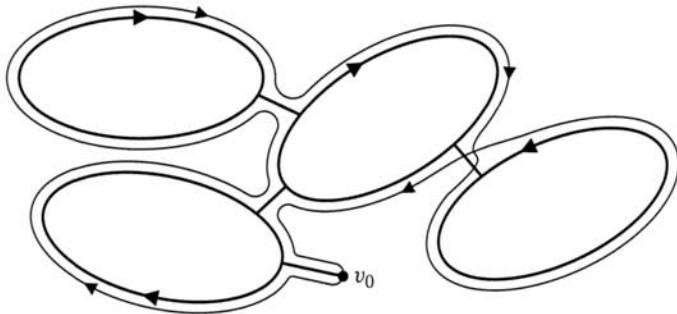
**Remark:** To the extent that we do not always obtain the best inequalities, the introduction of the mass and comass is not really necessary, since they are equivalent to the norms defined in an analogous way starting with the Euclidean norm on  $T_v^*V$ . Nevertheless, the mass and comass help to see that for  $p > 2$ , the quotient norm on  $H_p(V; \mathbb{R})$  is not Euclidean in general, even if  $V$  is  $S^2 \times S^2$  or a flat torus.

**4.20. The Hurewicz homomorphism.** In one dimension, the Hurewicz homomorphism (see [Hur–Wall], p. 148) is easy to visualize: Let  $\ell: S^1 \rightarrow V$  be a loop based at a point  $v \in V$ . The various ways to triangulate  $S^1$  enable us to associate with  $\ell$  an integral 1-chain whose mass equals the length of  $\ell$ . Additionally, the homology class of this chain depends only on the homotopy class of  $\ell$ , so that the *Hurewicz homomorphism*  $h: \pi_1(V, v) \rightarrow H_1(V; \mathbb{Z})$  is well defined.

**4.20<sub>2+</sub><sup>1</sup> Comparison between the length and the mass.** Assume  $V$  is connected, fix a point  $v_0 \in V$  and recall the (length) norm  $V$  on the fundamental group  $\pi_1(V, v_0)$  which measures each class of loops in  $\pi_1(V, v_0)$  by the length of the shortest representative. Now, we pass this norm to  $H_1(V)$  via the Hurewicz homomorphism by defining  $\text{length}(\alpha)$  for  $\alpha \in H_1(V)$  as the infimum of lengths of the loops in  $V$  based at  $v_0$  which represent (i.e., are homologous to)  $\alpha$ . Clearly, this length majorizes the mass  $\|\alpha\| = \|\alpha\|_{H_1}$  as the definition of the latter allows a representation of  $\alpha$  by a possibly *disconnected* collection of closed curves in  $V$ . It is equally obvious that  $\text{length}(\alpha) \leq C\|\alpha\|_{H_1}$  for some constant  $C = C_V$ , since every collection of closed curves can be replaced by a single one in the same homotopy class without drastically increasing the total length. Moreover, we have the following sharpening of this.

**4.20<sub>2+</sub><sup>1</sup>bis<sub>+</sub> Lemma:** If  $V$  is compact, then there exists a function  $C(\ell) = C_V(\ell)$  satisfying  $C(\ell) \rightarrow 0$  for  $\ell \rightarrow \infty$  such that

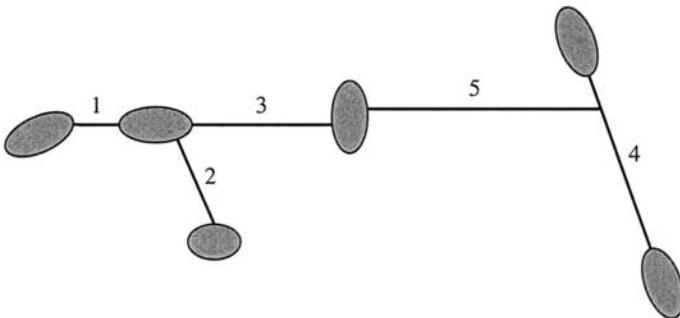
$$1 \leq \text{length}(\alpha)/\|\alpha\|_{H_1} \leq 1 + C(\text{length}(\alpha)). \quad (\circ)$$



**Proof.** What we need is a system of bridges connecting a collection of closed curves in  $V$ , so that the total length of these bridges is small compared to the sum of the lengths of the curves. Since all curves may be assumed to be noncontractible, their total length is at most a constant times (number of components), and so our claim follows from:

**4.20 $\frac{2}{3}$  Sublemma:** *Every collection of  $N$  connected subsets in  $V$  can be connected by geodesic segments of total length  $\leq \text{const}_V N^{1-1/n}$ ,  $m = \dim V$ .*

**Proof.** Every nonempty subset in  $V$  has the  $\varepsilon$ -neighborhood of volume  $\geq \varepsilon^n$ , and so there is an edge of length  $\leq N^{-1/n}$  between some pair of our subsets. Then there is an edge of length  $\leq (N-1)^{1/n}$  between the resulting  $N-1$  connected subsets, and so on.



Their total length is  $\leq \sum_{i=1}^N i^{-1/n} \simeq N^{1-1/n}$  for  $n \geq 1$  and the proof follows with a special (trivial) consideration of the case  $\dim V = 1$ .

**Remarks**  $\pm$ : (a) Since the curves in question have diameters  $\geq \delta > 0$ , their  $\varepsilon$ -neighborhoods have volumes  $\geq \delta \varepsilon^{n-1}$ , and so one can bound  $C(\ell)$  by  $C(\ell) \leq \text{const}_V \ell^{-1/(n-1)}$  for  $n \geq 2$  (where the case  $n = 2$  needs a little extra care).

(b) The original version of the lemma (4.20bis in the French edition) claimed an even stronger bound,  $C(\ell) \leq \text{const}_V \ell^{-1}$ , which amounts to

$$\text{length}(\alpha) - \|\alpha\| \leq \text{const}_V, \quad (\square)$$

but the accompanying proof was incorrect. Nevertheless, the inequality  $(\square)$  is valid and follows trivially from a theorem due to D. Burago cited in 3.16 which implies that

$$\text{length}(\alpha) \leq \|\alpha\|_{H_1}^{\lim} + \text{const}_V, \quad (\Delta)$$

where the limit norm equals, as we know,  $\|\alpha_{\mathbb{R}}\|$ . We suggest that the reader prove  $(\square)$  independently of  $(\Delta)$ , but I must admit that I have no recollection of whether such an argument is easily given.

**4.21. The Jacobi variety.** Here we will assume that the group  $H_1(V; \mathbb{Z})$  has no torsion, so that it can be considered as a lattice within  $H_1(V; \mathbb{R})$  equipped with its stable norm. We will denote by  $\langle , \rangle$  the duality pairing between  $H_1(V; \mathbb{R})$  and  $H^1(V; \mathbb{R})$ .

Now let  $E$  be a vector space of closed 1-forms representing the cohomology  $H^1(V; \mathbb{R})$  (in [Lichn],  $E$  is the space of harmonic forms, but we want to maintain a purely differential point of view). We can then identify  $E^*$  with  $H_1(V; \mathbb{R})$ . Given  $v \in V$ , we define a map  $\tilde{f}$  from the set  $C_v$  of paths in  $V$  starting at  $v$  into  $E$  by

$$\langle \tilde{f}(c), \alpha \rangle = \int_c \alpha$$

for  $c \in C_v$  and  $\alpha \in E$ .

If  $c, c'$  have the same endpoint  $x$ , then

$$\int_c \alpha - \int_{c'} \alpha = \int_{c - c'} \alpha = \int_{\gamma} \alpha,$$

where  $\gamma$  is the homology class of  $c - c'$ . The set of linear forms on  $E$  given by  $\alpha \mapsto \int_{\gamma} \alpha$  identifies via biduality with  $H_1(V; \mathbb{Z})$ .

Thus, if we identify paths in  $C_v$  having the same endpoint, the mapping  $\tilde{f}$  induces a mapping  $f$  of  $V$  into the torus  $H_1(V; \mathbb{R})/H_1(V; \mathbb{Z})$ . *A priori*, the map  $f$  depends on the choice of  $v$  and  $E$ , but a change of the space  $E$

representing  $H^1(V; \mathbb{R})$  transforms  $f$  into a mapping that is homotopic to  $f$ .

The torus  $J_1 = H_1(V; \mathbb{R})/H_1(V; \mathbb{Z})$  is called the *Jacobi variety* of  $V$ , and the map  $f$  (well defined up to homotopy) is the *Jacobi mapping*. If  $V$  is equipped with a Riemannian metric, then we equip  $\mathbb{T}$  with the left-invariant Finsler metric induced by  $\|\cdot_{\mathbb{R}}\|$ . If  $H_1(V; \mathbb{Z})$  has torsion, then we take the lattice  $H(V; \mathbb{Z})/\text{torsion} \subset H_1(V; \mathbb{R})$  instead of  $H_1(V; \mathbb{Z})$  and define the torus  $J_1$  as earlier.

The object of the next proposition is to geometrically approximate the Jacobi variety of  $V$ , which was presented so far in a rather formal manner.

**4.22<sub>+</sub>**. Consider the self-coverings of the Jacobian torus  $J_1 = J_1(V) (= \mathbb{T}^d$  for  $d = \text{rank } H_1(V)$ ) given by  $t \mapsto mt$ ,  $m = 1, 2, 3, \dots$ , and let  $\tilde{V}_m \rightarrow V$  be the induced covering of a compact manifold  $V$  with  $\text{rank}_{\mathbb{R}} H_1(V) = d$ , where we think of  $V$  as being mapped to  $J_1 = H_1(V; \mathbb{R})/H_1(V; \mathbb{Z})$  via the Jacobi mapping. Notice that the fundamental group of this covering  $\pi_1(\tilde{V}_m) \subset \pi_1(V)$  is generated by

1. the commutator  $[\pi_1(V), \pi_1(V)]$ ,
2. all  $m$ -th powers  $\gamma^m \in \pi_1(V)$ ,
3. all  $\gamma$  which are torsion modulo commutator (i.e., the torsion in  $H_1(V)$ ).

Now we take the induced path metric in the covering  $\tilde{V}_m \rightarrow V$ , scale it by  $m^{-1}$ , and let  $m \rightarrow \infty$ .

**Proposition:** *The metric spaces  $m^{-1}\tilde{V}_m$  Hausdorff-converge to the Jacobian (torus)  $J_1$  of  $V$  with the metric coming from the  $\mathbb{R}$ -mass  $\|\cdot_{\mathbb{R}}\|$  on its universal covering  $\tilde{J} = H_1(V; \mathbb{R})$ .*

**Proof.** The above lemma trivially implies that the space (group)  $H_1(V)$  with the metric length( $\alpha - \beta$ ) converges, after scaling, to  $H_1(V; \mathbb{R})$  in the pointed Hausdorff topology,

$$m^{-1}H_1(V) \xrightarrow{\text{Hau}} H_1(V; \mathbb{R})$$

for  $m \rightarrow \infty$ , where one should keep in mind that our  $H_1(V; \mathbb{R})$  with the metric  $\|(\alpha - \beta)\|$  is scale-invariant. This  $H_1(V)$  can be seen geometrically in the abelian covering  $\tilde{V}_{\text{Ab}} \rightarrow V$  induced by the universal covering  $H_1(V; \mathbb{R}) = \tilde{J}_1 \rightarrow J_1$ . Notice that  $\tilde{V}_{\text{Ab}} \rightarrow V$  is the maximal Galois covering with a free abelian Galois (i.e, deck transformation) group, which is  $\mathbb{Z}^d = H_1(V; \mathbb{Z})/\text{torsion}$ . Thus, the  $\mathbb{Z}^d$  orbit in  $\tilde{V}_{\text{Ab}}$  of the lifted reference point

$v_0 \in V$  identifies with the group  $\mathbb{Z}^d = H_1(V; \mathbb{Z})/\text{torsion}$  with the length norm (induced from  $H_1(V; \mathbb{Z})$  under the factorizing away the torsion).

Next, we observe that  $(H_1(V; \mathbb{Z}), \text{length})$  and  $(\mathbb{Z}^d, \text{length})$  are both separated by a bounded Hausdorff distance. Since  $(\mathbb{Z}^d, \text{length})$  is an orbit of cocompact action in  $\tilde{V}_{\text{Ab}}$ , it also has finite distance from  $\tilde{V}_{\text{Ab}}$ . Thus,

$$m^{-1}\tilde{V}_{\text{Ab}} \xrightarrow{\text{Hau}} H_1(V; \mathbb{R}) = \tilde{J}_1,$$

where ‘‘Hau’’ refers to the pointed Hausdorff topology.

Finally, we observe that

$$\tilde{V}_m = \tilde{V}_{\text{Ab}}/m\mathbb{Z}^d,$$

and so  $m^{-1}(\tilde{V}_m) = (m^{-1}\tilde{V}_{\text{Ab}})/m\mathbb{Z}^d$  converge to  $(m^{-1}\tilde{J}_1)/m\mathbb{Z}^d = \tilde{J}_1/\mathbb{Z}^d$ .

**4.23<sub>+</sub>**. Notice that the proof provides nontrivial geometric information about every mapping  $f: V \rightarrow J_1$  in the Jacobi homotopy class, or rather about the corresponding covering map  $\tilde{f}: \tilde{V}_{\text{Ab}} \rightarrow \tilde{J}_1 = H_1(V; \mathbb{R})$ , where  $\tilde{V}_{\text{Ab}}$  is given the path metric  $\text{dist}$  induced from  $V$ . Namely, we (obviously) have the following

**4.24<sub>+</sub> Lemma:** *The map  $\tilde{f}$  is isometric at infinity,*

$$\widetilde{\text{dist}}(\tilde{v}_1, \tilde{v}_2)/\|(\tilde{f}(v_1) - \tilde{f}(v_2)\| \rightarrow 1$$

as  $\text{dist}(\tilde{v}_1, \tilde{v}_2) \rightarrow \infty$ . Moreover, it admits a (discontinuous) almost inverse map  $\varphi: \tilde{J}_1 \rightarrow \tilde{V}_{\text{Ab}}$ , such that  $\text{dist}(\varphi \circ f - \text{id}) \leq \text{const} < \infty$  and  $\text{dist}(f \circ \varphi - \text{id}) \leq \text{const} < \infty$ . In other words,  $f$  is a quasi-isometry with implied bi-Lipschitz constant equal to one at infinity.

**4.25. Definition:** Let  $W$  be a manifold equipped with a metric  $d_i$  not necessarily induced by a Riemannian structure. We define the *volume* of  $W$  as

$$\sup_g \left\{ \text{vol}(W, g) : \begin{array}{l} g \text{ is a Riemannian metric on } W \text{ whose} \\ \text{distance function } \text{dist}_g \text{ is smaller than } d_i \end{array} \right\}.$$

When  $W = J_1$ , the distance  $d$  is translation invariant, and so it suffices to consider the supremum over translation-invariant Riemannian metrics, i.e., those metrics arising from a Euclidean norm on  $H_1(V; \mathbb{R})$ . The supremum is then attained, since the function  $\|\cdot\| \mapsto \text{vol}(J_1, \|\cdot\|)$  is continuous on the space of Euclidean norms on  $H_1(V; \mathbb{R})$ .

**4.26. Remark:** The notion of volume defined in 4.25 differs in general from the  $n$ -dimensional Hausdorff measure of  $W$ , for example, as well as from other reasonable notions of volume (see [Fed]GMT, Ch. 2, sec. 10).

**4.27. Theorem:** *If  $V$  is oriented,  $\text{rank } H_1(V) = n = \dim(V)$ , and the Jacobi mapping  $f: V \rightarrow J_1$  has nonzero degree, then*

$$\text{vol}(V) \geq \text{vol}(J_1). \quad (*)$$

**Remarks:** (a) The hypothesis that  $\deg(f) \neq 0$  indicates that the fundamental class of  $V$  is the product of  $n$  classes of degree 1, a condition that only pertains to the topology of  $V$  and not to its metric.

(b+) In 4.29 $\frac{1}{2}$ , we will prove the optimal inequality

$$\text{vol } V \geq \text{vol}_+ J_1 \quad (+)$$

for

$$\text{vol}_+ J_1 = \inf_g \{\text{vol}(J_1, g)\},$$

where the infimum ranges of Riemannian metrics  $g$  on  $J_1$  whose distance function is greater than the metric on  $J_1$  corresponding to the  $\mathbb{R}$ -mass  $\|\cdot_{\mathbb{R}}\|$  on  $H_1(V; \mathbb{R}) = \tilde{J}_1$ .

The proof of Theorem 4.27 is modeled on that of the following lemma (which won't be used but whose interest is worth the pain of bringing it up):

**4.28. Generalized Besicovitch Lemma ([Der]).** *Let  $K$  be a Riemannian cube and denote by  $(F_i, G_i)$ ,  $1 \leq i \leq n$ , its pairs of opposite faces. If  $d_i$  is the distance between  $F_i$  and  $G_i$ , then*

$$\text{vol}(K) \geq \prod_{i=1}^n d_i.$$

**Proof.** For  $x \in K$  we set  $f_i(x) = d(x, F_i)$  and  $f = (f_1, \dots, f_n): K \rightarrow \mathbb{R}^n$ . We will show that  $K' \subset f(K)$ , where  $K' = \prod_{i=1}^n [0, d_i] \subset \mathbb{R}^n$ .

By hypothesis,  $K$  is a cube, i.e., there exists a homeomorphism  $h: K \rightarrow K'$  such that  $h|_{\partial K}: \partial K \rightarrow K'$  maps each face onto a face. In other words, if  $y_i$  is the  $i$ -th coordinate in  $\mathbb{R}^n$ , then  $y_i \circ h(F_i) = 0$  and  $y_i \circ h(G_i) = d_i$ . However,  $y_i \circ f(F_i) = 0$  and  $y_i \circ f(G_i) = f(G_i) > d_i$ , and so by setting  $f_t(x) = (1-t)f(x) + th(x)$ , we obtain a homotopy from  $f|_{\partial K}$  to  $h|_{\partial K}$  with values in  $\mathbb{R}^n \setminus K'$ . If there exists  $y \in K' \setminus f(K)$ , then we have just shown that  $f|_{\partial K}$  is homotopic to  $h|_{\partial K}$  in  $\mathbb{R}^n \setminus y$ , and thus is a generator

of  $[\partial K, \mathbb{R}^n \setminus y]$ . But  $f|_{\partial K}$  extends to a map  $f: K \rightarrow \mathbb{R}^n \setminus y$ , i.e.,  $f|_{\partial K}$  is homotopic to 0 in  $\mathbb{R}^n \setminus y$ , a contradiction.

To complete the proof, we approximate  $f$  by smooth maps. It is clear that each function  $f_i: K \rightarrow (\mathbb{R}, \text{can})$  is short; for each  $\varepsilon > 0$  there exists a  $C^\infty$  mapping  $f_{i,\varepsilon}$  such that  $d(f_i, f_{i,\varepsilon}) \leq \varepsilon/n$  and  $\text{dil}(f_{i,\varepsilon}) \leq 1 + \varepsilon$ . Arguing as above, we find that the image of  $f_\varepsilon = (f_{1,\varepsilon}, \dots, f_{n,\varepsilon})$  contains the set  $K'_\varepsilon = \prod_{i=1}^n (\varepsilon, d_i + \varepsilon)$ . If  $\omega_0$  is the volume form on  $(\mathbb{R}^n, \text{can})$ , then  $\omega_0 = dy_1 \wedge \dots \wedge dy_n$ , and so  $f_\varepsilon^* \omega_0 = \bigwedge_{i=1}^n f_\varepsilon^* dy_i = \bigwedge_{i=1}^n df_{i,\varepsilon}$ . From this, we can deduce that  $\|f_\varepsilon^* \omega_0\| \leq (1 + \varepsilon)^n$ , and so

$$\begin{aligned} \text{vol}(K) &\geq (1 + \varepsilon)^{-n} \int_K \|f^* \omega_0\| \nu_g \geq (1 + \varepsilon)^{-n} \left| \int_K f^* \omega_0 \right| \\ &\geq (1 + \varepsilon)^{-n} \left| \int_{f(K)} \omega_0 \right| \geq (1 + \varepsilon)^{-n} \prod_{i=1}^n (d_i - 2\varepsilon) \end{aligned}$$

for each  $\varepsilon > 0$ .

**4.28bis. Remark:** There is another version of Besicovitch's lemma that applies to connected manifolds  $(M, g)$  whose boundary has two components  $\partial M_1, \partial M_2$ . If  $d$  is the distance  $d(\partial M_1, \partial M_2)$  and  $a$  is the infimum of the masses (cf. 4.17) of cycles homologous to  $\partial M_1$ , then  $\text{vol}(g) \geq ad$ .

**4.29. Proof of Theorem 4.27.** Fix a Euclidean norm  $\|\cdot\|_e$  on  $H_1(V; \mathbb{R})$  that is strictly smaller than  $\|\cdot\|_{\mathbb{R}}$ , so that  $f^0: V^0 \rightarrow (H_1(V; \mathbb{R}), \|\cdot\|_e)$  is “short at infinity” by Lemma 4.24. Choose a parallelepiped  $K_0$  in the Euclidean space  $(H_1(V; \mathbb{R}), \|\cdot\|_e)$  and denote by  $(F_i^0, G_i^0)$  its pairs of opposite faces,  $d_i = d(F_i^0, G_i^0)$  with respect to the Euclidean distance  $\|\cdot\|_e$ , and  $K_1$  the homothetic  $kK_0$ , where  $k$  is an integer. Set  $K = (f^0)^{-1}(K_1)$ ,  $F_i = (f^0)^{-1}(kF_i^0)$ , and  $G_i = (f^0)^{-1}(kG_i^0)$ . If  $\varepsilon > 0$ , then for sufficiently large  $k$  we have  $d(F_i, G_i) \geq (1 + \varepsilon)^{-1}kd_i$ . For  $x \in K$ , set  $g_i(x) = d(x, F_i)$ ,  $g = (g_1, \dots, g_n): K \rightarrow (\mathbb{R}^n, \text{can})$ , and

$$K' = \prod_{i=1}^n (0, (1 + \varepsilon)^{-1}kd_i) \subset \mathbb{R}^n.$$

Modulo an isometry  $E \rightarrow \mathbb{R}^n$  sending  $K_0$  onto  $(1 + \varepsilon)^n K'$ , we may assume that  $f^0$  takes values in  $\mathbb{R}^n$  and  $f^0(\partial K) \cap K' = \emptyset$ . As in the preceding lemma, it turns out that that  $f^0|_{\partial K}$  is homotopic to  $g|_{\partial K}$  in  $\mathbb{R}^n \setminus K'$ . However,  $f$  has nonzero degree, and consequently,  $f^0$  assumes almost every value in  $K'$  so that  $f^0|_{\partial K}$  is not homotopic to 0 in  $\mathbb{R}^n \setminus y$  for  $y \in K'$ . The same is true

for  $g$ , so that  $K' \subset g(K)$  and, since  $g: K \rightarrow \mathbb{R}^n$  is short,

$$\text{vol}(K) \geq \text{vol}(g(K)) \geq (1 + \varepsilon)^{-n} \prod_{i=1}^n k d_i = (1 + \varepsilon)^{-n} \text{vol}(K_1)$$

in  $E$ .

Choose a basis of  $H_1(V; \mathbb{Z})$ . The parallelepiped  $P$  (not necessarily a rectangle for  $\|\cdot\|_e$ ) thus determined is a fundamental domain for the action of  $H_1(V; \mathbb{Z})$ , and so  $\text{vol}((\mathbb{T}, \|\cdot\|_e)) = \text{vol}(P)$ . If  $k$  is sufficiently large, then the parallelepiped  $K_1 = kK_0$  contains a number  $N$  of translates of  $P$  and is contained within a union of  $N(1 + \varepsilon)$  of translates of  $P$ . Since  $f^0$  is bijective on fibers, the set  $Q = (f^0)^{-1}(P)$  is a fundamental domain for the action of  $\text{Aut}(V)$ , and so

$$\text{vol}((f^0)^{-1}(K_1)) \leq N(1 + \varepsilon) \text{vol}(V)$$

$$\text{vol}(K_1) \geq N \text{vol}(P) = N \text{vol}((\mathbb{T}, \|\cdot\|_e)),$$

and so finally

$$\begin{aligned} \text{vol}(V) &\geq (N(1 + \varepsilon))^{-1} \text{vol}(K) \\ &\geq \frac{1}{N}(1 + \varepsilon)^{-n-1} \text{vol}(K_1) \\ &\geq (1 + \varepsilon)^{-n-1} \text{vol}(P), \end{aligned}$$

from which we can conclude that  $\text{vol}(V) \geq \text{vol}((\mathbb{T}, \|\cdot\|_e))$  for every Euclidean norm on  $H_1(V; \mathbb{R})$  less than  $\|\cdot\|_R$ , hence  $\text{vol}(V) \geq \text{vol}((\mathbb{T}, \|\cdot\|_R))$ .

**4.29<sub>2+</sub><sup>1</sup>. Remarks, conjectures, exercises.** (a) Observe the following basic topological fact underlying the proof of the Besicovitch lemma.

**Surjectivity lemma:** *Let  $\varphi$  be a self-mapping of a compact polyhedron  $P$  which sends each face of  $P$  into itself. Then the map  $\varphi$  is onto.*

In fact, this map is homotopic to the identity via face-preserving maps, and so  $\varphi$  maps each face of  $P$  into itself with *degree one*, which implies surjectivity.

(b) There are various versions of Besicovitch's lemma bounding the volume of a polyhedron from below in terms of the distances between the faces. For example, if  $\Delta^n$  is a simplex with a riemannian metric, such that the sum of the  $n+1$  distances from each point in  $\Delta^n$  to the  $(n-1)$ -faces of  $\Delta^n$  is  $\geq \delta$ , then

$$\text{vol } \Delta^n \geq \mu_n(\delta) = \mu_n(1)\delta^n,$$

where  $\mu_n(\delta)$  denotes the volume of the regular Euclidean  $n$ -simplex

$$\Delta_\delta^n = \{x_i \geq 0 : \sum_{i=0}^n x_i = \delta\}$$

of height  $\delta$ .

**Proof.** Map  $\Delta^n$  to  $\mathbb{R}_+^{n+1}$  by the  $n + 1$  distance functions to the  $(n - 1)$ -faces of  $\Delta^n$  and then radially project to  $\Delta_\delta^n$ . This sends  $\Delta^n$  onto  $\Delta_\delta^n$  with  $|\text{Jacobian}| \leq 1$ . In fact, every map  $x: V \rightarrow \mathbb{R}^2$  with coordinate functions  $x_i(v)$  has

$$|\text{Jacobian}(v)| \leq \left( n^{-n} \left( \sum_{i=1}^q \|dx_i(v)\|^2 \right)^n \right)^{1/2},$$

i.e., the differential  $D = D_v(x): T_v(V^n) \rightarrow \mathbb{R}^q$  satisfies

$$[\det(D^*D)]^{1/2} \leq [n^{-n} (\text{trace } D^*D)^n]^{1/2},$$

by the arithmetic-geometric mean inequality. (See §7.3 in [Gro]FRM for further examples of a similar kind.)

(c) Since the map  $\tilde{f}: \tilde{V}_{\text{Ab}} \rightarrow \tilde{J}_1 = H_1(V; \mathbb{R})$  is isometric at infinity, the inequality  $\text{vol } V \geq c \text{vol } J_1$  is equivalent, for every  $c > 0$ , to the (asymptotic) lower bound on the volumes of large  $R$ -balls  $\tilde{B}(R)$  in  $\tilde{V}_{\text{Ab}}$  by those of the balls  $B(R)$  in  $\tilde{J}_1 = H_1(V; \mathbb{R})$  with the mass norm,  $\liminf_{R \rightarrow \infty} \text{vol } \tilde{B}(R) / \text{vol } B(R) \geq c$ . This is seen by covering large balls by fundamental domains. On the other hand, since  $\tilde{J}_1 = H_1(V; \mathbb{R})$  is a normed space, and every norm  $\|\cdot\|$  can be minorized by a Euclidean norm  $\|\cdot\|_e$  satisfying  $\|\cdot\|_e \geq \|\cdot\|/\sqrt{d}$  for  $d = \text{rank } H_1(V)$  by the F. John theorem (see [John] and [Mil–Sch]). This makes  $\text{vol } B(R) \geq d^{-d/2} \nu_d R^d$ , where  $\nu_d$  denotes the volume of the unit ball in  $\mathbb{R}^d$ , and consequently, under the assumptions of 4.27

$$\liminf_{R \rightarrow \infty} R^{-n} \text{vol } \tilde{B}(R) \geq n^{-n/2} \nu_n.$$

The unfortunate coefficient  $n^{-n/2}$  was removed in a recent paper by Burago and Ivanov (see [Bur–Iv]<sub>AV</sub> and [Bur–Iv]<sub>RT</sub>), who used the full power of John's theorem. This says that

there is a (unique) Euclidean norm  $\|\cdot\|_e^+$  on a given  $d$ -dimensional normed space  $(H, \|\cdot\|)$  such that  $\|\cdot\|_e^+ \geq \|\cdot\|$  and

$$(\|\cdot\|_e^+)^2 = \sum_{i=1}^q \ell_i^2,$$

where  $\ell_i$  are some linear forms on  $X$  depending on  $\|\cdot\|$  which satisfy  $\sum_{i=1}^q \|\ell_i\|^2 \leq d$ .

This theorem of F. John yields the following (minor generalization of) the result by Burago-Ivanov:

(d) **Theorem:** *Let  $X$  be an  $n$ -dimensional Riemannian manifold and let  $H = (H, \|\cdot\|)$  be a normed space. Suppose that there exists a proper, asymptotically short map  $F: X \rightarrow H$ , i.e., such that*

$$\limsup_{\text{dist}(x,y) \rightarrow \infty} \frac{\|F(x) - F(y)\|}{\text{dist}(x,y)} \leq 1.$$

*If  $\dim H = n$  and  $F$  has nonzero degree mod 2, then  $F$  is asymptotically volume-increasing for the volume (element)  $\text{vol}_+$  in  $H$  associated to some Euclidean norm  $\|\cdot\|_e^+$  on  $H$  majorizing  $\|\cdot\|$ ,*

$$\liminf_{R \rightarrow \infty} \frac{\text{vol } F^{-1}(B(R))}{\text{vol}_+ B(R)} \geq 1.$$

*Furthermore, if  $V$  is oriented, then*

$$\liminf_{R \rightarrow \infty} \frac{\text{vol } F^{-1}(B(R))}{\text{vol}_+ B(R)} \geq |\deg(F)|,$$

*where  $B(R)$  are the  $\|\cdot\|$ -balls in  $H$ ,*

$$B(R) = \{h \in H : \|h\| \leq R\}.$$

**Proof.** We “transplant” the linear function  $\ell_i$  from  $H$  to  $X$  as follows. First, we compose each  $\ell_i$  with  $F$  and restrict the resulting functions on  $X$  to some  $\rho$ -separated  $\rho$ -net  $X_\rho \subset X$ . If  $\rho$  is large, then these functions are  $\lambda_i$ -Lipschitz on  $X_\rho$  for  $\lambda_i \approx \|\ell_i\|$ , i.e., they are  $(\|\ell_i\| + \varepsilon(\rho))$ -Lipschitz with  $\varepsilon(\rho) \rightarrow 0$  as  $\rho \rightarrow \infty$ . Then the functions  $\ell_i \circ F$  extend from  $X_\rho$  to  $\lambda_i$ -Lipschitz functions  $\tilde{\ell}_{i,\rho}$  on  $X$ , which clearly satisfy

$$\sup_{x \in X} |\tilde{\ell}_{i,\rho}(x) - \ell_i \circ F(x)| \leq C\rho$$

for  $C = \max \|\ell_i\|$ . Thus, the map  $\tilde{L}_\rho = (\tilde{\ell}_{1,\rho}, \tilde{\ell}_{2,\rho}, \dots, \tilde{\ell}_{q,\rho}): X \rightarrow \mathbb{R}^q$  lies within a bounded distance from  $L \circ F: X \rightarrow \mathbb{R}^q$  for  $L = (\ell_1, \dots, \ell_q)$  and so the filling volume of  $\partial F^{-1}(B(R)) = F^{-1}(\partial B(R))$  mapped to  $\mathbb{R}^q$  is roughly the same as that for  $\partial B(R)$  mapped to  $\mathbb{R}^q$  by  $L$ , i.e., the difference between the two is  $o(R^n)$  as  $R \rightarrow \infty$ . (This can be seen from the perspective of §7.3

in  $[Gro]_{\text{FRM}}$  or by just normally projecting  $\mathbb{R}^q$  onto the image  $L(H) \subset \mathbb{R}^q$ .) On the other hand, the Jacobian of  $\tilde{L}_\rho$  is bounded by

$$\left( n^{-n} \left( \sum_{i=1}^q \lambda_i^2 \right)^n \right)^{1/2} = \left( n^{-n} \left( \sum_{i=1}^q \|\ell_i\|^2 \right)^n \right)^2 + o(1) \leq 1 + o(1)$$

for  $\rho \rightarrow \infty$ . It follows that the volume of  $F^{-1}(B(R))$  is “essentially” greater than the filling volume of  $\partial B(R) \subset L(H) \subset \mathbb{R}^N$ , which obviously equals  $\text{vol}_+(B(R))$  (where one should not take “filling” too seriously, since the action can be moved to  $L(H)$  via the normal projection  $\mathbb{R}^q \rightarrow L(H)$ ). Finally, we erase “essentially” by letting  $R \rightarrow \infty$  and then  $\rho \rightarrow \infty$ .

(d<sub>1</sub>) **Corollary (see [Bur–Iv]):** *If the map  $F$  is isometric at infinity, e.g.,  $X = \tilde{V}_{\text{Ab}}$  and  $F$  equals the cover  $\tilde{f}$  of a Jacobian map  $f$  from  $V = X/\mathbb{Z}^n$  to a  $J_1 = H_1(V; \mathbb{R})/\mathbb{Z}^n$ ,  $\mathbb{Z}^n = H_1(V; \mathbb{R})/\text{tor}$ , then the balls  $\tilde{B}(R)$  about a fixed point  $x_0$  in  $X$  satisfy*

$$\liminf_{R \rightarrow \infty} R^{-n} \text{vol } \tilde{B}(R) \geq \nu_n |\deg(f)| \quad (*)$$

(where  $\nu_n$  denotes the volume of the unit Euclidean  $n$ -ball).

(d<sub>2</sub>) **Rigidity.** It is clear from the above that equality in  $(*)$  implies that the norm  $\|\cdot\|$  in  $H$  equals the Euclidean (John’s) norm  $\|\cdot\|_e^+$ , i.e.,  $(H, \|\cdot\|)$  is Euclidean to start with. Furthermore, the composition  $\overline{F}_\rho$  of  $\tilde{F}_\rho$  with the normal projection  $\mathbb{R}^q \rightarrow \mathbb{R}^n = L(H)$  is *almost isometric on average*. This means that among all pairs of points  $\{x, y \in B(R) : \text{dist}(x, y) \leq 1\}$ , those which satisfy

$$|\text{dist}(x, y) - \|\overline{F}_\rho(x) - \overline{F}_\rho(y)\| | \geq \varepsilon > 0$$

have the *relative measure*  $\leq \delta_\rho$  in  $B(R)$  for all sufficiently large  $R$ , where  $\delta_\rho \rightarrow 0$  for every fixed  $\varepsilon > 0$  and  $\rho \rightarrow \infty$ . It then trivially follows (compare Ch. 2.E<sub>+</sub>) that there exists a sequence of points  $x_i \in X$  such that  $(X, x_i)$  Hausdorff-converge to  $\mathbb{R}^n$  with the maps  $\overline{F}_\rho$  converging to isometries along with  $\rho \rightarrow \infty$ . In particular, if the isometry group is cocompact on  $X$ , e.g.,  $X = \tilde{V}_{\text{Ab}}$  for a compact  $V$ , then  $X = \mathbb{R}^n$  (see [Bur–Iv]). (This obviously remains true if  $X$  comes along as a *minimal leaf* of a compact foliation.)

(d<sub>3</sub>) **Technical remarks.** (i) When  $F$  is isometric at infinity, one can produce the  $\tilde{L}$ -companion of  $L$  more constructively, in the spirit of the argument in 4.29 (see also [Bur–Iv]). Namely, for each  $i = 1, \dots, q$ , one could take the pullback  $y_i = (\ell_i \circ F)^{-1}(0) \subset X$  and set

$$\tilde{\ell}_i = \pm \|\ell_i\| \text{dist}(x, y_i)$$

with the  $\pm$  sign determined by  $\text{sign}(\ell_i \circ F(x))$ .

(ii) When  $X$  is isometrically acted upon by  $\mathbb{Z}^n$  (e.g.,  $X = \tilde{V}_{\text{Ab}}$ ), then one can average the differentials  $d\tilde{\ell}_i$  over this action, thus getting measurable closed 1-forms  $\tilde{\delta}_i$  on  $X/\mathbb{Z}^n$  cohomologous to the corresponding forms  $\delta_i$  on  $H/\mathbb{Z}^n$  coming from  $\ell_i$ . These forms allow an alternative proof of the rigidity result, since they provide an isometry  $X/\mathbb{Z}^n \rightarrow H/\mathbb{Z}^n$  sending each  $\delta_i$  to  $\tilde{\delta}_i$  (an exercise for the reader). One may wonder if these  $\tilde{\delta}_i$  are good for something else.

(e) **About (+).** The inequality

$$\text{vol } V \geq \text{vol}_+ J_1 \quad (+)$$

now follows from the Burago–Ivanov theorem by 4.24<sub>+</sub>. Furthermore, if the Jacobian map  $f: V \rightarrow J_1$  has degree  $> 1$ , then

$$\text{vol } V \geq c_n |\deg f| \text{vol}_+ J_1$$

for some universal constant  $c_n > 1$ . This follows by confronting our present arguments with those in Ch. 2.E<sub>+</sub>. (Notice that  $\deg f$  equals the minimal integer  $> 0$  such that the cup product of arbitrary classes  $h_i \in H_1(V; \mathbb{Z})$ ,  $i = 1, \dots, n$ , is divisible by  $d$  without being zero.)

(f) **Exercises.** (i) Let  $X_j$ ,  $j = 1, 2, \dots$  be compact  $n$ -dimensional manifolds which Hausdorff-converge to a compact Finsler manifold  $Y$ , such that all  $X_j$  are uniformly (in  $j$ ) locally contractible. Show that

$$\liminf_{j \rightarrow \infty} \text{vol } X_j \geq \text{vol}_+ Y,$$

where equality implies that  $Y$  is Riemannian (compare [Bur-Iv]).

(ii) Consider a proper asymptotically Lipschitz map  $F: X \rightarrow H$  where  $n = \dim X > \dim H = d$  and let  $\text{systdeg}(f)$  (systolic degree) denote the infimum of  $(d - n)$ -volumes of cycles in  $X$  homologous to the pullback of a regular value of  $F$  (assuming  $F$  is smooth around some point in  $H$ ). Prove that

$$\liminf_{R \rightarrow \infty} \frac{\text{vol}_n F^{-1}(B(R))}{\text{vol}_+ B(R)} \geq \text{systdeg}(f)$$

and study the case of equality.

(g) Let  $X$  be a complete Riemannian manifold and define  $\text{supVol}(R)$  as the supremum of volumes of the  $R$ -balls in  $X$ . One dreams of a universal lower bound  $\text{supVol}(R) \geq \text{const } R^n$  (especially for  $\text{const} = \nu_n$ ) for all  $R$

(especially for  $R \rightarrow 0$  and  $R \rightarrow \infty$ ) under suitable geometric and topological assumptions on  $X$ , such as uniform contractibility (see [Gro]FRM and 4.44 below for some evidence in favor of such conjectures). Here one knows that uniformly contractible surfaces satisfy  $\sup \text{vol}(R) \geq 3R^2$  for all  $R \geq 0$  (an exercise for the reader, also see 5.2.A in [Gro]FRM) and one (naively?) expects  $\sup \text{vol } R \geq \pi R^2$  in this case. Particular  $X$ 's where one wants to know  $\sup \text{vol } B(R)$ , besides universal coverings of compact aspherical manifolds, are *contractible minimal* leaves of compact foliations, e.g., stable and unstable Anosov leaves, such as the horospheres of (compact) manifolds with negative curvature. Do the latter have (at least) Euclidean volume growth?

**4.30<sub>+</sub> Theorem:** *Let  $V$  be a closed Riemannian  $n$ -manifold which admits  $n-1$  dimensional cohomology classes in  $H^1(V; \mathbb{R})$  with nonzero cup-product. If  $\text{rank } H_1(V; \mathbb{R}) = n = \dim V$ , then there is a nontorsion class  $\alpha \in H_1(V; \mathbb{Z})$  such that*

$$\|\alpha_{\mathbb{R}}\| \leq \nu^{-1/n} 2(\text{vol}(V))^{1/n}, \quad (++)$$

where  $\nu_n \approx n^{-n/2}$  denotes the volume of the unit Euclidean ball.

**Proof.** First let  $V$  be a flat Riemannian torus. Then (++) holds for some nontrivial  $\alpha \in H_1(V)$  by the *Minkowski theorem*. In fact, the required short loop comes along with the minimal simply-connected (Euclidean!) ball  $B(R) \subset V (\simeq T^n)$  which has

$$\nu_n R^n = \text{vol } B(R) \leq \text{vol } V$$

and thus delivers a loop of length  $2R$ . Now, we invoke the inequality (+) above, which says that the volume  $\text{vol } V$  majorizes that of the Jacobian with the Riemannian metric coming from  $\|\cdot\|_e^+$  on  $\tilde{J} = H_1(V; \mathbb{R})$ , where we recall that  $\|\cdot\|_e^+ \geq \mathbb{R}\text{-mass}$  on  $H_1(V; \mathbb{R})$ . Thus, the general case follows from the Minkowski theorem above applied to

$$J_1 = (H_1(V; \mathbb{R}), \|\cdot\|_e^+)/H_1(V; \mathbb{Z}).$$

**4.31<sub>+</sub> Remarks.** (a) We had a weaker inequality with an extra  $\sqrt{n}$  factor in the French edition of this book, since Burago-Ivanov's refinement of (\*) was only conjectural at that time.

(b) Our argument actually shows that

$$\|\alpha_{\mathbb{R}}\| \leq \sigma_n (\text{vol } V)^{1/n},$$

where the number  $\sigma_n < 2\nu_n^{-1/n}$  equals the length of the minimal geodesic  $\gamma$  in the “worst” flat torus of unit volume, where  $\text{length}(\gamma)$  is the largest possible. In fact, everything about the  $\mathbb{R}$ -mass on  $H_1(V; \mathbb{Z})$  can be bounded (in terms of  $\text{vol } V$ ) by what happens to flat tori.

(c) The discussion above generalizes Loewner’s theorem (see 4.1 above) since the stabilized norm  $\| \cdot_{\mathbb{R}} \| = \| \cdot \|_{\text{lim}}$  on  $H_1(V; \mathbb{Z})$  equals the original length according to the following.

**4.32. Lemma:** *If a curve  $\alpha$  in an orientable surface  $S$  is length minimizing in its homotopy class, then its iterates  $\alpha^p$  are length minimizing in their respective homotopy classes.*

**Proof.** Indeed, the lift  $\tilde{\alpha}$  of  $\alpha$  to the universal cover  $\tilde{S}$  of the surface is an infinite geodesic that divides  $\tilde{S}$  into two domains. A loop  $\beta$  based on  $\alpha$  and having minimal length in some multiple of the class of  $\alpha$  would have a lift  $\tilde{\beta}$ , which, unable to intersect  $\tilde{\alpha}$  without being nonminimizing, would lie on one side of  $\tilde{\alpha}$ . In this case, however,  $\tilde{\beta}$  would have at least one self-intersection, which would permit us to shorten it within its homotopy class. Thus,  $\alpha = \beta$ .

**4.33<sub>+</sub> Additional remarks and exercises.** (a) Our reasoning can be adjusted to the more general situation where  $\text{rank } H_1(V) \geq n = \dim V$ , but this brings an extra constant depending on  $\text{rank } H_1$  (see §7.4, 7.5 in [Gro]FRM). On the other hand, we shall later see from a different angle that one can always find a short curve which is nonhomologous to zero in  $V$  and for which the implied constant depends only on  $n = \dim V$ . Probably this could also be achieved with a refinement of our argument.

(b) Suppose that  $d = \text{rank } H_1(V) < n = \dim V$ , define  $\text{systdeg}(f)$  of the Jacobian map  $f: V \rightarrow J_1 = \mathbb{T}^d$  as above, and prove the following bound on the mass of the minimal  $\alpha \in H_1(V; \mathbb{Z})$  generalizing (++),

$$\|\alpha_{\mathbb{R}}\|^{n-d} \text{systdeg}(f) \leq \nu_n^{-1} 2^n \text{vol } V.$$

(c) Extend the logic of the exercise (b) to the Jacobian mapping of the Heisenberg manifold  $H_{2n+1}/\Gamma$  to  $\mathbb{T}^{2n}$  with a homotopy version of  $\text{systdeg}$  (compare 7.4.C' in [Gro]FRM).

(d) **Question.** Consider  $H_{2n+1}$  with its canonical contact structure and look at the Carnot-Caratheodory metrics on  $H_{2n+1}$  compatible with this structure. Are there reasonably general conditions on such metrics which would ensure the lower asymptotic bound on the CC-volumes of the  $R$  balls

in such  $H_{2n+1}$  by  $\text{const}_n R^{2n+2}$ ? In particular, we want such bounds for (reasonable?) CC-metrics invariant under a cocompact nilpotent isometry group  $\Gamma$  acting on  $H_{2n+1}$ .

## D. An application of geometric integration theory

**4.34. A dual norm on cohomology.** If we represent the cohomology of a manifold  $V$  by differential forms  $\omega$ , then by proceeding as in 4.15, we obtain a norm on  $H^p(V; \mathbb{R})$  by setting

$$\|\eta\| = \inf\{M^*(\omega) : \omega \in \eta\}$$

for each  $\eta \in H^p(V; \mathbb{R})$ . Indeed,  $d\Omega^{p-1}$  is a closed subspace of  $\Omega^p$ , as follows from the fact that exact forms are those having zero integral over any cycle.

Even though the duality of the norms  $M$  and  $M^*$  takes place on the level of chains and forms, and not on the level of cycles and closed forms, the quotient norms on  $H_p(V; \mathbb{R}), H^p(V; \mathbb{R})$  are still dual to one another. In other words,

**4.35. Proposition:** *For each class  $\alpha \in H^p(V; \mathbb{R})$ , we have*

$$\|\alpha\| = \sup\{|\omega(\alpha)| : \|\omega\| \leq 1\}.$$

**Proof.** (See also [Fed]VP, 4.10). The fact that  $\sup\{|\omega(\alpha)| : \|\omega\| \leq 1\}$  follows from the inequality  $|\omega(\alpha)| \leq \|\omega\| \|\alpha\|$  that is itself a consequence of the same inequality for forms  $\eta$  representing  $\omega$  and cycles  $c$  representing  $\alpha$ .

To prove the reverse inequality, we consider a cycle  $c_0$  representing  $\alpha$  and a linear form  $L$  on  $B_p \oplus \mathbb{R}c_0$  (here,  $B_p$  denotes the space of  $p$ -dimensional boundaries) defined by  $L(B_p) = 0$  and  $L(c_0) = \|\alpha\|$ . Since  $B_p$  is  $M$ -closed in the space of chains (as follows from the fact that a chain  $c$  is a boundary precisely when  $\int_c \eta = 0$  for each  $C^\infty$  closed form  $\eta$ ),  $L$  is continuous on  $B_p \oplus \mathbb{R}c_0$  and has norm less than 1. By the Hahn–Banach theorem, there exists an extension of  $L$  (which we will also denote by  $L$ ) having norm  $\leq 1$  to the space of chains.

Thus,  $L$  is a  $M$ -continuous, co-closed co-chain (since it vanishes on  $B_p$ ), and so by [Whit], p. 157, 261, it can be represented by a measurable, bounded differential form  $\eta$ , and by 4.16 and 4.17 we have  $\|L\| = M^*(\omega)$ . If  $\omega$  is the class of  $\eta$ , defined by smoothing  $\eta$ , we have

$$\omega(\alpha) = \|\alpha\| \quad \text{and} \quad \|\eta\| \leq 1.$$

From this duality we can deduce “stable” isoperimetric inequalities of the form of those in Section 4.C, providing a partial answer to Question 4.13.

**Theorem 4.36** *For every Riemannian metric  $g$  on  $\mathbb{C}\mathbb{P}^n$ , a generator  $\alpha$  of  $H_2(\mathbb{C}\mathbb{P}^n; \mathbb{Z})$  satisfies the inequality*

$$\|\alpha_{\mathbb{R}}\|^n \leq n! \operatorname{vol}(\mathbb{C}\mathbb{P}^n, g).$$

**Proof.** Let  $\omega$  be a generator of  $H_2(\mathbb{C}\mathbb{P}^n; \mathbb{Z})$ . Then  $\omega^n$  is a generator of  $H_{2n}(\mathbb{C}\mathbb{P}^n; \mathbb{Z})$ , and for each 2-form  $\eta$  representing  $\omega$ , we have

$$1 = \int_{\mathbb{C}\mathbb{P}^n} \eta^n \leq n! M^*(\eta)^n \operatorname{vol}(\mathbb{C}\mathbb{P}^n, g),$$

from which we conclude that  $1 \leq n! \|\omega\|(\mathbb{C}\mathbb{P}^n, g)$ . By 4.34, however (here we use the duality between the 1-dimensional spaces  $H_2(\mathbb{C}\mathbb{P}^n; \mathbb{Z}), H^2(\mathbb{C}\mathbb{P}^n; \mathbb{Z})$ ),  $\|\alpha\| = 1/\|\omega\|$ .

**4.37. Remarks:** We have the same inequalities for  $\mathbb{H}\mathbb{P}^n$  and  $\mathbf{Ca}\mathbb{P}^n$  (cf. [Berger]Pu); the preceding proof uses only the fact that one has a manifold  $V$  of dimension  $an$  with  $H^a(V; \mathbb{Z}) = \mathbb{Z}$ , such that the  $n$ -th power of a generator of  $H^a(V; \mathbb{Z})$  is a generator of  $H^{an}(V; \mathbb{Z})$ .

The case of  $\mathbb{C}\mathbb{P}^n$  is particularly nice, thanks to the reduction of 2-forms and the resulting Wirtinger inequality (cf. [Fed]GMT, p. 40). The inequality of Theorem 4.36 includes  $n!$  since the  $n$ -th power of the form is taken and not  $(2n)!/2^n$ , which is the best constant for the comass of the product of  $n$  arbitrary 2-forms (cf. [Fed]GMT, Ch. 1, or [Whit], Ch. 1).

For the same reason, this inequality is optimal: If  $\mathbb{C}\mathbb{P}^n$  is equipped with a Kähler metric, then the norms  $\|\cdot\|$  and  $\|\cdot_{\mathbb{R}}\|$  on  $H^2(\mathbb{C}\mathbb{P}^n; \mathbb{Z})$  coincide and the geometric invariants  $m(g)$  and (cf. 4.13)  $\nu(g)$  are those of the standard metric.

Of course, on  $\mathbb{R}\mathbb{P}^n$ , where the homology is completely torsion, the real homology is zero and this technique produces nothing. On the other hand, it is particularly well adapted to product spaces.

**4.38. Theorem:** *There exists a constant  $C(m, n) > 0$  such that each metric  $g$  on  $S^m \times S^n$  ( $m \neq n$ ) satisfies the following. For classes  $\alpha, \beta$  from the factor spaces,*

$$\operatorname{vol}(g) \geq C(m, n) \|\alpha_{\mathbb{R}}\| \|\beta_{\mathbb{R}}\|.$$

*For each  $k, n$ , there exists a constant  $D(k, n) > 0$  such that each metric  $g$  on  $V = S^k \times \cdots \times S^k$  ( $n$  factors) satisfies  $\operatorname{vol}(g) \geq D(k, n)A$ , where we set*

$$A = \inf\{\|\alpha_{\mathbb{R}}\| : \alpha \in H(V; \mathbb{Z}) \setminus 0\}.$$

**Remark:** For  $m = 1$ , we recover Theorem 4.30 when  $V = \mathbb{T}^n$ .

**Proof.** The first part of the assertion is proved as in the proof of Theorem 4.36. The second proceeds as follows. The real vector space  $H_m(V; \mathbb{R}) = E$  has dimension  $n$  and contains  $H_m(V; \mathbb{Z})$  as a lattice. We equip  $E$  with the norm  $\|\cdot\|$  introduced in 4.17 and denote by  $K$  the convex, symmetric set that defines this norm, i.e.,  $K = \{x \in E : \|x\| \leq 1\}$ . We equip  $E^* = H^m(V, \cdot)$  with the norm  $\|\cdot\|^*$  introduced in 4.15 and set  $K^* = \{f \in E^* : \|f\|^* \leq 1\}$ ,  $\Lambda^* = H^m(V, \mathbb{Z})$ . By definition,  $\Lambda^*$  is the dual lattice of  $\Lambda$ , i.e.,

$$\Lambda^* = \{f \in E^* : (f(x)) \in \mathbb{Z} \text{ for all } x \in \Lambda\}.$$

The duality described in Proposition 4.35 for the norms  $\|\cdot\|$  and  $\|\cdot\|^*$  implies that the convex sets  $K, K^*$  are *reciprocal* (or *polar*).

**4.39. Lemma:** *For  $A = \inf\{\|x\| : x \in \Lambda \setminus \{0\}\}$ , there always exists a basis  $(t_i)_{i=1,\dots,n}$  of  $\Lambda^*$  such that*

$$\prod_{i=1}^n \|t_i\|^* A^n \leq (n!)^2 \left(\frac{3}{2}\right)^{\frac{1}{2}(n-1)(n-2)}.$$

**Proof.** The proof consists of the combination of three classical results of geometric number theory to conclude that

1.  $\text{vol}(K) \text{vol}(K^*) \geq (n!)^{-2} 4^n$ ,
2. There exists a basis  $(t_i)_{i=1,\dots,n}$  of  $\Lambda^*$  such that

$$\prod_{i=1}^n \|t_i\|^* \text{vol}(K^*) \leq 2^n \left(\frac{3}{2}\right)^{\frac{1}{2}(n-1)(n-2)}.$$

3.  $\text{vol}(K)A^n \leq 2^n$ .

Since  $E, E^*$  are arbitrary, we can set  $E = E^* = \mathbb{R}^n$  and  $\Lambda = \Lambda^n = \mathbb{Z}^n$ . In [Lekerk], the proof of (1) appears on p. 106 in 14.2, (2) on p. 59 of 10.2, and finally (3) on p. 33 of 5.1. Note that the volumes are taken with respect to Lebesgue measure and therefore disappear when we take the product of the three inequalities!

**End of the proof of Theorem 4.38.** Choose exterior differential  $n$ -forms  $\omega_i$  such that  $\|\omega_i\| = \|t_i\|^*$  for  $i = 1, \dots, n$ , so that, as in Theorem 4.36, we have

$$1 = \int_V \omega_1 \wedge \cdots \wedge \omega_n \leq \prod_{i=1}^n \|\omega_i\| \nu(g).$$

See [Gro]FRM and [Heb] for further results in this direction.

**Question:** What are the best constants and extremal manifolds for all these inequalities?

## E<sub>+</sub> Unstable systolic inequalities and filling

**4.40.** The notion of a *systole*  $\text{syst}_k(V)$  suggested by M. Berger refers to the minimal volume of a  $k$ -cycle *nonhomologous to zero* in a Riemannian manifold  $V$ , and for  $k = 1$  one may also speak of *homotopy  $k$ -systoles* corresponding to minimal *noncontractible* curves in  $V$ . A general bound on the latter is known for all closed *aspherical* manifolds  $V$ , i.e., those having *contractible* universal coverings  $\tilde{V}$ . This includes, for example, manifolds homeomorphic to the torus  $\mathbb{T}^n$  or those admitting metrics of nonpositive sectional curvatures. Moreover, such a bound on  $\text{syst}_1$  remains valid for all *essential*  $n$ -dimensional manifolds and polyhedra  $V$ , where a polyhedron  $V$  is called  *$n$ -essential* if there exists an aspherical (possibly infinite) polyhedron  $K$ , and a continuous map  $V \rightarrow K$  which does not contract to the  $(n - 1)$ -skeleton of  $K$ .

**4.41. Theorem:** *Every compact  $n$ -dimensional  $n$ -essential polyhedron with a piecewise Riemannian metric admits a noncontractible curve  $S_1$  with*

$$\text{length } S_1 \leq C_n (\text{vol})^{1/n}$$

*for some universal constant  $C_n > 0$ .*

See Appendix 2 in [Gro]FRM for a proof and [Gro]SII for an introductory survey of the subject.

**Remarks:** (a) A basic case of the theorem concerns a closed manifold  $V$  for which the classifying map  $V \rightarrow K(\Pi; 1)$  for  $\Pi = \pi_1(V)$  and  $K(\Pi; 1)$  being the (aspherical!) Cartan-Eilenberg space, is nonhomologous to zero. For example, the real projective space  $\mathbb{RP}^n$  is essential since it is nonhomologous to zero in  $K(\mathbb{Z}_2; 1) = \mathbb{RP}^\infty$ . Thus, the theorem above generalizes Pu's result, albeit *not* with a sharp constant.

(b) One does not truly need the “piecewise Riemannian” condition. The conclusion of the theorem remains true for an arbitrary metric on  $V$  with the  $n$ -dimensional Hausdorff measure instead of the volume. (This needs a minor adjustment of the argument in [Gro]FRM.)

**4.42.** To get a grasp on 4.41, let us start with an aspherical space  $K$  which is given a metric with the homotopy systole  $\geq \sigma > 0$ . This means that every curve in  $K$  of length  $< \sigma$  is contractible. This also can be seen in the universal covering  $\tilde{K}$  of  $K$ : for every point  $\tilde{k} \in \tilde{K}$  and every *nontrivial* deck transformation  $\gamma \in \pi_1(K)$  acting on  $\tilde{K}$ , one has

$$\text{pathdist}(\tilde{k}, \gamma(\tilde{k})) \geq \sigma.$$

Notice that we do not even assume that our metric on  $K$  is a path metric. Nevertheless, “pathdist” makes sense as the infimum of lengths of curves in  $\tilde{K}$  (between  $\tilde{k}$  and  $\gamma(\tilde{k})$ ) where this length is measured in the metric on  $K$  after projecting the curves to  $K$ . So, we do not exclude the possibility  $\text{pathdist} = \infty$ .

By appealing to our theorem, we then claim that every  $n$ -dimensional cycle  $V$  in  $K$  nonhomologous to zero, satisfies

$$\text{vol}(V) \geq \varepsilon_n \sigma^n \quad (\geq)$$

for some universal constant  $\varepsilon_n > 0$  (i.e.,  $\varepsilon_n = c_n^{-n}$  for the  $c_n$  above). Here,  $V$  is a *singular cycle*, i.e., an integer combination of singular simplices which are continuous maps  $\varphi_i : \Delta^n \rightarrow K$ . The volume of such  $V = \sum_i k_i \varphi_i$  is defined to be  $\leq t$  if there exist piecewise Riemannian metrics  $g_i$  on  $\Delta^n$  such that all  $\varphi_i$  are 1-Lipschitz on  $(\Delta^n, g_i)$  and  $\sum_i |k_i| \text{vol}(\Delta^n, g_i) \leq t$ . And  $\text{vol } V \geq t$  means that such  $g_i$  *do not* exist.

The idea for proving the lower bound on  $\text{vol } V$  comes from geometric measure theory, where one knows that *minimal*  $n$ -dimensional subvarieties tend to have large(!) volumes. For example, if  $V$  is a complete, minimal subvariety in  $\mathbb{R}^N$ , then the  $R$ -balls in  $V$  around some point  $v \in V$  grow *faster* with  $R$  than with the balls in the flat  $\mathbb{R}^n$ . And one knows that this property of  $V$  (called “volume monotonicity”) depends on the classical *filling* (also called *isoperimetric*) *inequality* in  $\mathbb{R}^N$ ,

*every*  $(n-1)$ -cycle  $S$  in  $\mathbb{R}^N$  *bounds* an  $n$ -chain  $B$  with

$$\text{vol}_n(B) \leq \text{const}_n(\text{vol}_{n-1} S)^{n/(n-1)}. \quad (*)$$

And a similar inequality in  $K$  along with a suitable existence theorem of *minimal* cycles  $V$  in a given homology class would imply  $(\geq)$  by a rather simple argument.

Actually, the filling idea was already used in 4.6+, where we were cutting away long fingers from a surface  $V$  and then filling in by spherical caps, which played the role of the  $B$  above in the sense of  $(\geq)$ . That can be generalized from surfaces to all dimensions with the following

**Filling inequality:** Let  $S$  be an (oriented)  $(n-1)$ -dimensional pseudomanifold (i.e., a possibly singular variety where the singularity has codimension  $\geq 2$  so that  $S$  makes an abstract cycle) with a piecewise smooth Riemannian metric. Then  $S$  can be filled in by an (oriented) pseudomanifold  $B$  of dimension  $n$  with boundary, i.e., the boundary  $\partial B$  is identified with  $S$ , and then  $B$  can be given a piecewise Riemannian metric with the following three properties:

1. The distance function restricted from  $B$  to  $S$  equals the distance function of the original metric on  $S$ .
2. The volume of  $B$  is bounded by

$$\text{vol}_n(B) \leq c_n (\text{vol}_{n-1} S)^{n/(n-1)}$$

for some constant in the interval  $0 < c_n < n^n \sqrt{n!}$ .

3. The distance from each point  $b \in B$  to  $\partial B = S$  satisfies

$$\text{dist}(b, S) \leq c'_n (\text{vol}_{n-1} S)^{1/(n-1)}$$

for  $0 < c'_n < n^{n+1} \sqrt{n!}$ .

This is proved in [Gro]FRM. Here, one should note that once we are granted  $B$  satisfying (1) and (2), it can be easily improved (by cutting away long fingers) in order to also satisfy (3). On the other hand, (3) alone leads to a bound on the 1-systole of an aspherical manifold  $V$ . Namely, we fill-in  $V$  instead of  $S$  by some  $(n+1)$ -dimensional pseudomanifold  $W$  (instead of  $B$ ) satisfying (1) and (2). Then, assuming that all short curves in  $V$  are contractible, we could construct by a rather trivial topological argument a retraction of  $W$  to  $V = \partial W \subset W$ . But this clearly is impossible, and so short, noncontractible curves in  $V$  must exist. (We suggest that the reader try this by him/herself, or consult [Gro]FRM for details.)

**Remark:** We had to introduce pseudomanifolds to bypass the cobordism problem for manifolds. Alternatively, we could work with a filling  $W$  homeomorphic to  $V \times [0, \infty)$  with some *complete* metric satisfying (1) and (2), but certainly *not* (3).

**4.43. Filling volume and filling radius.** The filling inequality concerns two basic metric invariants of a Riemannian manifold  $V$ .

- I. **Filling Volume.** This is the infimal  $t$  such that  $V$  can be filled by  $W$  (with  $\partial W = V$  satisfying (1), i.e., having  $\text{dist}_W|_V = \text{dist}_V$  and  $\text{vol}_{n+1} W = t$ ).

**II. Filling Radius.** Defined as the infimal  $R$  such that  $V$  can be filled by  $W$  satisfying (1) and having  $\text{dist}(w, V) \leq R$  for all  $w \in W$ .

**Exercise.** Show that this definition of FilRad agrees with the one given in 3.35 via the Kuratowski embedding of  $V$  into the space of functions on  $V$ .

**4.44. Filling noncompact manifolds and uniform contractibility.** The notions of FilVol and FilRad generalize to complete, noncompact Riemannian manifolds, and the noncompact filling inequalities follow easily from the compact one above. An amusing application concerns *uniformly contractible* Riemannian manifolds  $V$  (also called *geometrically contractible* in [Gro]FRM). This means that there exists a *contractibility function*  $R(r) = R_V(r)$  such that every  $r$ -ball in  $V$  can be contracted within a concentric  $R(r)$ -ball (compare Ch. 3.E<sub>+</sub>).

**Theorem:** *Every complete, uniformly contractible manifold  $V$  has infinite volume.*

This can be easily reduced to a bound on the (noncompact) filling radius of  $V$  issuing from the (compact) bound stated in 4.42. We leave this to the reader, who is referred to [Gro]FRM, [Katz]<sub>RFR</sub>, and the papers by M. Katz cited in [Gro]<sub>SII</sub> for a further study of FilRad and FilVol. Here we indicate several unsolved

**Problems.** (a) What is FilVol  $S^n$ ? One suspects that the minimal filling is achieved with the hemisphere  $S_+^{n+1} \supset \partial S_+^{n+1} = S^n$ , but this is unknown even for  $n = 1$ . Notice that the difficulty in the case of  $S^1$  is due to the possibly nontrivial topology of a surface  $W$  with  $\partial W = S^1$ . Such a  $W$  of positive genus (but not for genus  $W = 0$ ) may have  $\text{Area } W < \text{Area } S_+^2 = 2\pi$ , where we insist that  $\text{dist}_W|_{S^1} = \text{dist}_{S^1}$ .

(b) Does the largest ball of radius  $R$  in a *uniformly contractible* manifold  $V$  have  $\text{vol } B(R) \geq \text{const}_n R^n$  for  $n = \dim V$ ? (Compare 4.29 $\frac{1}{2}$  and [Gro]FRM).

(c) Does every closed manifold  $V$  with *positive scalar curvature*  $Sc(V) \geq \delta > 0$  have

$$\text{FilRad}(V) \leq \text{const}_n \delta^{-1/2}?$$

(d) What are the true constants in the general systolic and filling inequalities, and what are the extremal manifolds? Does, for example, the standard  $\mathbb{R}P^n$  have minimal volume per given systole? (One may ask the same question for flat tori, but it is harder to believe that any of them is systolically extremal for  $n \geq 3$ .)

**Remarks:** Most techniques employed for bounding  $\text{syst}_1$  and related invariants do not discriminate between Riemannian and Finslerian metrics, since they rely only on the Banach geometry of  $L_\infty$  spaces (see [Gro]FRM). But then there is little chance to arrive at extremal objects and best constants in the Riemannian category. One should try instead some  $L_2$ -techniques better adapted to the Riemannian needs (compare [Bur–Iv] and [B–C–G] for successful proofs of *sharp* volume inequalities).

**4.45. On higher dimensional systoles.** There are easy examples of  $n$ -manifolds  $V$  where  $\text{syst}_1 \text{syst}_{n-1}$  is much bigger than  $\text{vol}(V)$ . For instance, if a simply-connected manifold  $V_0$  admits a free isometric action of  $S^1$ , then  $V = (V_0 \times \mathbb{R})/\mathbb{Z}$  for a suitable free cyclic subgroup, i.e., copy of  $\mathbb{Z}$  in  $S^1 \times \mathbb{R} \subset \text{Isom}(V_0 \times \mathbb{R})$ , may have an arbitrarily large ratio  $\text{syst}_1 \text{syst}_{n-1} / \text{vol}$ . Just rotate  $V_0$  by a small angle  $\alpha = 2\pi/i$ , translate  $\mathbb{R}$  by  $\varepsilon \simeq \alpha^2$ , and observe that

1. the shortest noncontractible curve in  $V$  has

$$\text{length} = \text{syst}_1 \geq \alpha$$

2. the minimal  $(n-1)$ -cycle has

$$\text{vol} = \text{syst}_{n-1} = \text{vol } V_0.$$

Since  $\text{vol } V$  obviously equals  $\varepsilon \text{vol } V_0$ , we get

$$\text{syst}_1 \text{syst}_{n-1} / \text{vol} \simeq \alpha/\varepsilon = i \rightarrow \infty.$$

One can play further with such examples, dressing the essential geometric core with various topological garments via a suitable surgery. Probably one can produce in this way a metric with given systoles in dimensions  $\geq 2$  on every topological manifold or polyhedron (see [Berger]Sys and Appendix D<sub>+</sub>). But one's curiosity may not yet be satisfied, since these represent only a tiny slice of possible geometries, and one starts wondering about how typical the examples above actually are. And if one tries something different, one finds that it is unexpectedly hard to evaluate systoles of even the simplest manifolds, such as compact homogeneous spaces.

**Test question.** Determine the possible range of the systolic vector

$$s = s(g) = (s_1, s_2, s_3, \dots, s_{n-3}, s_{n-2}, s_{n-1}, s_n),$$

$n = m^2$ , for  $s_i = \text{syst}_i(U(m), g)$ , where  $g$  runs over all *left-invariant* Riemannian metrics on the unitary group  $U(m)$ .

What is most interesting is to understand the asymptotic behavior of systoles as  $g$  goes to infinity by  $g \mapsto A^k g_0$  for some left invariant endomorphism  $A : T(U(m)) \rightarrow T(U(m))$  and  $k \rightarrow \infty$ . Nothing seems to be especially easy about the geometry of such spaces as  $(U(m), A^k g_0)$  for large  $k$  (compare [Gro]SII and [Gro]CC).

## F<sub>+</sub> Finer inequalities and systoles of universal spaces

**4.46. Bounding  $\text{syst}_1$  in the presence of extra topology.** Let  $V$  be a closed, aspherical Riemannian manifold. We seek inequalities of the form

$$\text{vol}(V)^{1/n} \geq |\text{Top}| \text{syst}_1(V), \quad (\text{Top})$$

where  $|\text{Top}|$  is some measure of the topological complexity of  $V$ . We have already met such an inequality for surfaces of genus  $\gamma$  with  $|\text{Top}| = \text{const } \sqrt{\gamma} / \log(\gamma)$ . This generalizes to higher dimensions with the *simplicial volume*  $\Delta = \Delta(V)$  defined in Ch. 5.F<sub>+</sub>. Namely, Top is valid with  $|\text{Top}| = \text{const}_n \Delta^{1/n} / \log(1 + \Delta)$ . To use this, we need examples of manifolds  $V$  with large  $\Delta$ . These are provided by manifolds  $V$  admitting Riemannian metrics with sectional curvature  $\leq -1$  and volumes  $\geq \delta$ , where  $\Delta \geq \varepsilon_n \delta$  for some universal  $\varepsilon_n > 0$ . Thus, *one cannot substantially increase the first systole of a manifold  $(V, g_0)$  with  $K(g_0) = -1$  by deforming  $g_0$  while keeping the volume  $(V, g_t)$  constant in  $t$*  (see [Gro]FRM).

Another Top-inequality relates  $\text{syst}_1$  to the sum  $b$  of all Betti numbers of  $V$ , where Top holds true with

$$|\text{Top}| = C_n b^{1/n} / \exp(C'_n \sqrt{\log(b)}),$$

while it is unknown with

$$|\text{Top}| = C_n b^{1/n} / \log(1 + b),$$

(see [Gro]SII for further discussion).

**4.47. Finding several short loops.** If  $V$  is essential and  $\text{vol}(V)$  is small, one may expect that there are several “independent” closed curves (possibly loops based at the same point in  $V$ ) of lengths  $\ell_1, \ell_2, \dots, \ell_k$ , where all the  $\ell_i$  are rather small, e.g.,

$$(\ell_1 \ell_2 \cdots \ell_k)^{n/k} \leq \text{const vol}(V)$$

(for  $k \leq n \leq \dim(V)$ ). More generally, one may take some class of metric graphs, i.e., 1-polyhedra with path metrics, say  $\Gamma = \{\gamma\}$ , and ask whether there is a short map of some  $\gamma$  to  $V$ , such that the image of  $\pi_1(\gamma)$  in  $\pi_1(V)$  has rank  $\geq k$  in a suitable sense. We refer to [Gro]FRM for results available in this direction, and here we look at this problem from the point of view of *universal spaces*.

**4.48. Systoles  $\text{syst}_n$  of canonical metrics on  $K(\Pi, 1)$  spaces.** Start with an abstract group  $\Pi$  and suppose we find some “canonical” metric space  $X$  with a (free) isometric  $\Pi$ -action. Then the  $n$ -th systole of the quotient space  $X/\Pi$  and the mass (or volume) norm on  $H_n(X/\Pi)$  in general, can be regarded as some “algebraic” invariant of  $\Pi$  defined by geometric means.

**Examples.** (a) Consider the unit sphere  $S^\infty$  in the space of bounded functions  $\mathbb{N} \rightarrow \mathbb{R}$  with the sup (i.e.,  $\ell_\infty$ ) norm. We give this sphere the induced path metric and make the group  $\mathbb{Z}_2$  act on  $S^\infty$  by the involution  $x \leftrightarrow -x$ . Thus, we obtain the projective space  $P^\infty = S^\infty/\mathbb{Z}_2$  with a “canonical” metric which, as we know, is a  $K(\mathbb{Z}, 1)$  space, from which it follows that  $H_i(P^\infty; \mathbb{Z}_2) = \mathbb{Z}_2$  for all  $i = 0, 1, \dots$ . Our basic systolic inequality trivially implies that

$$\text{syst}_k P^\infty \geq \varepsilon_k > 0,$$

and in fact, this is (trivially) equivalent to the bound on  $\text{syst}_1$  in manifolds  $V$  homeomorphic to  $\mathbb{RP}^n$  by  $\text{const}_n(\text{vol } V)^{1/n}$  (see [Gro]FRM).

(a') **Remark.** Notice that this  $P^\infty$  is Finslerian rather than Riemannian, and so there are many possibilities for defining the notion of volume (or mass) for  $k$ -cycles in  $P^\infty$ . These different volumes correspond to how we normalize the Lebesgue measure  $\mu$  in the  $k$ -dimensional normed spaces  $(H, \|\cdot\|)$ . One can use, for example, our volumes  $\text{vol}$  and  $\text{vol}_+$  from 4.25–27, or the Hausdorff measure for  $\|\cdot\|$ , etc. Of course, everything boils down to assigning a certain value to the measure  $\mu(B(1))$  of the unit  $\|\cdot\|$ -ball in  $V$ , and there are many (too many) *canonical* assignments of this  $\mu(B(1))$  (see [Gro]FRM for further discussion).

(a'') **Problem.** Determine the asymptotic behavior of  $\text{syst}_k P^\infty$  for  $k \rightarrow \infty$ . (The answer will certainly depend on a particular canonical mass $_k$  ( $\text{vol}_k$ ) we choose, and we may expect nice asymptotics only for judicious choices of this mass $_k$ .) The same question can be raised for  $P^\infty$  associated to an arbitrary “natural” infinite dimensional Banach space instead of  $\ell_\infty(\mathbb{N})$ , but the answer seems to be unknown for all except  $\ell_2$ .

(b) Let  $X$  be the unitary group  $U(\infty)$ , and let a group  $\Pi$  act on  $X$  via some unitary representation, say the regular one. This  $X$  comes along with the operator norm metric, and so the systolic question is well-posed. One knows by the *Kuiper's theorem* that  $X/\Pi$  is a  $K(\Pi; 1)$  space, and the general filling argument of [Gro]FRM seems to apply to this space. Thus, apparently

$$\text{syst}_n(X/\Pi) \geq \varepsilon_k > 0$$

for all  $k$ , where  $H_k(\Pi) \neq 0$ . Here again, one wishes to know more about the  $\text{syst}_k$ . Also, one may try different metrics on spaces of linear operators, such as the Hilbert-Schmidt or Schatten's  $\ell_p$ , but then one must be aware of the extra topology harbored by certain (smaller) groups of operators.

(c) **Uryson spaces revisited.** Let us pick up a set  $D$  of left invariant metrics on a group  $\Pi$  and consider all metric  $\Pi$ -spaces  $X$  where the metric on each orbit  $\text{dist}_X|_{\Pi(x)}$  belongs to our distinguished set  $D$ . Then one can construct as in 3.11 $_{3+}^2$  a universal space, say  $\mathcal{U} = \mathcal{U}(\Pi, D)$  such that

1.  $\mathcal{U}$  is a Polish metric space
2.  $\text{dist}_{\mathcal{U}} \Pi(u) \in D$  for all  $u \in \mathcal{U}$
3. Every  $\Pi$ -space  $X$  satisfying (1) and (2) admits an isometric  $\Pi$ -equivariant embedding into  $\mathcal{U}$ .
4. If  $X/\Pi$  is compact and  $Y \subset X$  is an invariant subset, then every equivariant isometric embedding  $Y \rightarrow \mathcal{U}$  extends to an equivariant isometric embedding  $X \rightarrow \mathcal{U}$ .

Next, one starts looking at  $\text{syst}_k(\mathcal{U}/\Pi)$  regarding these as certain invariants of  $(\Pi, D)$ . In particular, if  $D$  consists of all metrics satisfying  $\text{dist}(\pi_1, \pi_2) \geq 1$  for  $\pi_1 \neq \pi_2$ , then our basic systolic inequality in 4.41 is essentially equivalent to

$$\text{syst}_k(\mathcal{U}/\Pi) \geq \varepsilon_k > 0$$

whenever  $H_k(\Pi) \neq 0$ . And choosing different sets  $D$  often leads to finer results about short loops in essential polyhedra (see [Gro]FRM for an approach to this problem via a different class of universal spaces). And there is much left to be done in this field! (See 5.43 $_{3+}^+$  for different classes of universal spaces.)

**Systolic reminiscences.** I was exposed to metric inequalities in the late 60's by Yu. Burago, who acquainted me with the results of Loewner, Pu, and Besicovitch. These attracted me by the topological purity of their underlying assumptions, and I was naturally tempted to prove similar inequalities

in a more general topological framework, where the first steps had already been made by M. Berger (see our citations of [Berger]). Since the setting was so plain and transparent, I expected rather straightforward proofs based entirely on the coarea formula and/or product inequalities for exterior forms dualized with Hahn–Banach (as in the above Ch. 4.D). Having failed to find such a proof, I was inclined to look for counterexamples but realized to my surprise that the geometrically rather shallow co-area idea gets an unexpected boost from the topological (surgical) induction on dimension once the perspective has been shifted from systoles to the (isoperimetric) filling problem. This gave the desired bounds on  $\text{syst}_1 / (\text{vol})^{1/n}$  (albeit not with sharp constants) and encouraged a search for similar inequalities for  $\text{syst}_k$ ,  $k \geq 2$ .

On the other hand, if one wanted a counterexample, one needed a new geometric tool for bounding from below the volume of a  $k$ -cycle  $c$  in a riemannnan manifold where one had to forfeit the use of pointwise small closed  $k$ -forms with large integrals  $\int_C \omega$ , since this would also bound the  $\mathbb{R}$ -mass of  $C$ , in contradiction with the stable inequalities (see Ch. 4.D). Only belatedly (lecturing at the University of Maryland in the Spring of 1993) I realized that such a bound for  $k \geq 2$  could be reduced to that for  $k = 1$  with a variety of examples emerging via a geometric surgery applied to the innocuous-looking twisted product  $S^3 \times S^1$  (see 4.45) and further cartesian products  $(S^3 \times S^1) \times V'$  (see [Berger]Sys and Appendix D<sub>+</sub>). So the surgery proved useful for obtaining lower bounds on  $\text{syst}_k$  in *specific examples* as well as for obtaining upper bounds on  $\text{syst}_1$  for *general* (essential)  $(V, g)$ , thus giving us a rather clear view on the possible range of the systolic vector

$$g \mapsto (\text{syst}_1(g), \dots, \text{syst}_n(g) = \text{vol}(V, g)) \in \mathbb{R}^n$$

for a manifold  $V$  of a given homotopy type. And so the time came to look deeper into the geometry of spaces of metrics  $g$  with given systoles, or, even better, with a prescribed “volumic norm” on  $H_*(V)$  (see [Gro]SII for some preliminary questions and conjectures).

# Chapter 5

# Manifolds with Bounded Ricci Curvature

## A. Precompactness

In this chapter, we consider locally compact, pointed path metric spaces and the metric space structure on the collection of such spaces defined by the Hausdorff distance (or, more precisely, the uniform structure on this set defined by the family of Hausdorff distances on the balls of radius  $R$ ).

**5.1. Definition:** A family  $(X_i, x_i)$  of path metric spaces is *precompact* if, for each  $R > 0$ , the family  $B^{X_i}(x_i, R)$  is precompact with respect to the Hausdorff distance  $d_H$ .

**Observation:** For each  $\varepsilon > 0$  and  $R > 0$ , we denote by  $N(\varepsilon, R, X)$  the maximum number of disjoint balls of radius  $\varepsilon$  that fit within the ball of radius  $R$  centered at an  $x \in X$ . The function  $X \mapsto N(\varepsilon, R, X)$  is almost continuous; indeed, if  $d_H(B^X(x, R), B^Y(y, R)) < \delta$  and  $N(\varepsilon, R, X) = N$ , then there exist  $N$  points  $x_1, \dots, x_N$  in  $B^X(x, R)$  such that  $\text{dist}(x_i, x_j) > 2\varepsilon$  for  $i \neq j$ . This  $4\varepsilon$ -net induces a net  $y_i$  in  $B^Y(y, R)$  such that  $\text{dist}(y_i, y_j) > 2\varepsilon - 2\delta$  for  $i \neq j$ . Consequently,  $N(\varepsilon - \delta, R, Y) \geq N$  and conversely,  $N(\varepsilon - \delta, R, Y) \geq N(\varepsilon, R, Y)$ . In particular, the functions  $N(\varepsilon, R, \cdot)$  are bounded on every precompact family of path metric spaces.

**5.2. Proposition:** *A family  $(X_i, x_i)$  of pointed path metric spaces is precompact if and only if each function  $N(\varepsilon, R, \cdot)$  is bounded on  $(X_i)$ . In this case, the family is relatively compact, i.e., each sequence in the  $X_i$  admits a subsequence that Hausdorff-converges to a complete, locally compact path metric space.*

**Proof.** Fix  $\varepsilon > 0$  and  $R > 0$  and set  $N = \sup N(\varepsilon, R, X_i)$ . Using the hypothesis that  $N$  is finite, we must prove that there is a finite number of indices  $i_1, \dots, i_p$  such that, for each  $i$ , there exists  $j$  with

$$d_H(B^{X_i}(x_i, R), B^{X_{i_j}}(x_{i_j}, R)) \leq \text{const } \varepsilon.$$

To this end, it suffices to consider each subfamily  $N(\varepsilon, R, X_i) = n$  for  $1 \leq n \leq N$  individually, so that we may assume  $N(\varepsilon, R, X_i) = N$  for all  $i$ . In each ball  $B^{X_i}(x_i, R)$ , the maximal disjoint filling is realized by balls of radius  $\varepsilon$  centered at points of a  $2\varepsilon$ -net  $R_i$ . Indeed, if there exists a point  $y$  of  $B^{X_i}(x_i, R)$  located at a distance greater than  $2\varepsilon$  from each point of  $R_i$ , then the ball  $B(y, \varepsilon)$  would be disjoint from the balls  $B(x, \varepsilon)$  for  $x \in R_i$ , and therefore the net  $R_i$  would not be maximal. A choice of bijection  $f : \{1, \dots, N\} \rightarrow R_i$  induces a distance  $d_i$  on the set  $\{1, \dots, N\}$ . This function  $d_i : \{1, \dots, N\}^2 \rightarrow \mathbb{R}_+$  only assumes values between  $2\varepsilon$  and  $2R$  on the subset  $A$  of pairs of distinct integers, which has  $N^2 - N$  elements. Since the space  $[2\varepsilon, 2R]^{N^2 - N}$  is precompact in the product metric, there exist finitely many indices  $i_1, \dots, i_p$  such that, for each  $i$ , there is a  $j$  with

$$\sup_A |d_i(m, q) - d_{i_j}(m, q)| < \varepsilon^2,$$

and so

$$\sup_A \frac{d_i(m, q)}{d_{i_j}(m, q)} \leq \frac{1 + \varepsilon}{1 - \varepsilon},$$

that is,  $d_L(R_{i_j}, R_i) \leq \log((1 + \varepsilon)/(1 - \varepsilon))$ , where  $d_H(R_{i_j}, R_i) \leq R \log((1 + \varepsilon)/(1 - \varepsilon))$ . Finally,  $d_H(B^{X_i}(x_i, R), B^{X_{i_j}}(x_{i_j}, R)) \leq (2R + 4)\varepsilon$  approximately, which proves precompactness.

To prove compactness, we first assume that  $X_i$  is a sequence of path metric spaces of radius  $R$  and argue as above: We fix  $\varepsilon > 0$ , extract a subsequence such that  $N(\varepsilon, R, X_i) = N$ , construct the  $2\varepsilon$ -nets  $R_i$ , deduce from this the existence of functions  $d_i$  on  $A = \{(m, q) : m, q \leq N, m \neq q\}$ , and extract a subsequence  $d_{i_j}$  that converges to a distance on  $\{1, \dots, N\}$ . In order to apply a diagonal argument, we set  $Z_1 = X_{i_1}$  and  $R_1^1 = R_{i_1}$ , and note that  $R_1^1$  is a  $2\varepsilon$ -net in  $Z_1$  having Lipschitz distance less than  $\varepsilon/2$  from a distance  $d_1$  on  $\{1, \dots, N_1\}$ , where  $N_1 = \text{card}(R_1^1)$ . Now set  $Y_j = X_{i_j} \setminus U_\varepsilon(R_{i_j})$ , and let  $S_j$  be the set of centers of a maximal disjoint set of radius  $\varepsilon/2$  balls in  $Y_j$  that are pairwise disjoint relative to  $X$ . Using the fact that the  $X_j$  are path metric spaces, it is easy to check that  $R_{i_j} \cup S_j$  is an  $\varepsilon$ -net in  $X_{i_j}$  and that the radius  $\varepsilon/2$  balls centered on  $R_{i_j} \cup S_j$  are disjoint. It follows that  $\text{card}(R_{i_j}) + \text{card}(S_j)$  is bounded and therefore equal to some constant  $N_2$  for a subsequence  $X_{n_p}$ . For each  $p$ , we choose a bijection  $\{1, \dots, N_2\} \rightarrow R_{n'_p} \cup S_p$  extending the one from  $\{1, \dots, N_1\} \rightarrow R_{n_p}$  already

chosen. This bijection induces a distance  $d_{n_p}$  on  $\{1, \dots, N_2\}$ , and we can extract a subsequence  $X_{n'_p}$  such that the  $d_{n'_p}$  converge. Since the restrictions of the  $d_{n'_p}$  to  $\{1, \dots, N_1\}$  converge, the limit distance  $d_2$  extends  $d_1$ . We set  $Z_2 = X_{n'_0}$ ,  $R_2^1 = R_{n'_0}$ ,  $R_2^2 = R_2^1 \cup S_0$ , where  $n'_0$  is chosen so that  $\text{dist}\{d_2, d_{n'_0}\} \leq \varepsilon/4$ .

This procedure produces a subsequence  $Z_k$  of the  $X_i$ , a sequence  $N_k$  of integers, a distance  $d$  on  $\mathbb{N}$ , and a nested sequence of  $(\varepsilon/2^{i-2})$ -nets  $R_k^i$  in  $Z_k$ , having a Lipschitz distance less than  $\varepsilon/2^i$  from  $\{1, \dots, N_k\}$ . Since  $\{1, \dots, N_k\}$  is a  $(\varepsilon/2^{i-3})$ -net in  $(\mathbb{N}, d)$ , we conclude that  $Z_k$  tends to  $(\mathbb{N}, d)$  with respect to the Hausdorff distance (see Proposition 3.5). Finally, the completion  $\hat{\mathbb{N}}$  of  $(\mathbb{N}, d)$  is also a limit of the  $Z_k$  and, by Theorem 1.8, is therefore a locally compact path metric space.

For a family  $(X_i, x_i)$  of pointed spaces satisfying the hypotheses of the proposition, we can, again by a diagonal argument, extract a subsequence  $i_j$  such that the balls  $B^{X_{i_j}}(x_{i_j}, R)$  converge, which proves compactness for pointed convergence (Definition 3.14).

### 5.3. Theorem: The set of pointed Riemannian $n$ -manifolds satisfying the inequality

$$\text{Ricci}(g) \geq (n - 1)rg,$$

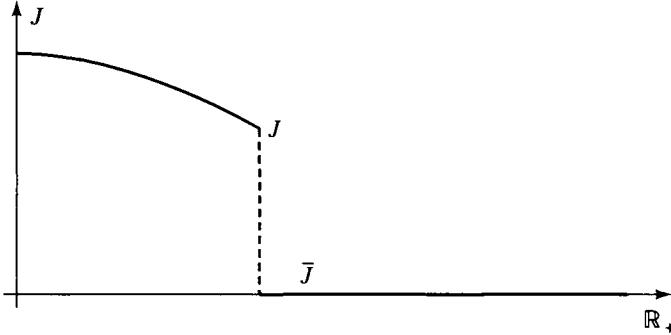
where  $g$  is the metric and  $r$  a real number, is precompact with respect to the pointed Hausdorff distance.

Indeed, Bishop's inequality enables us to bound the number of small balls within a large ball (cf. [Bish-Crit], p. 253): If  $V_r$  denotes the simply connected space of constant curvature whose Ricci curvature is equal to  $-(n - 1)rg$ , then Bishop's inequality states that for  $v \in V$ ,  $x \in V_r$ , if  $U \subset V$  is diffeomorphic via  $\exp_v$  to an open subset of  $T_v V$ , we can define a diffeomorphism  $f$  of  $U$  onto an open set of  $V_r$  by composing  $\exp_v^{-1}$  with an isometry of  $T_v V$  onto  $T_x V_r$  and subsequently with  $\exp_x: T_x V_r \rightarrow V_r$ . Then the Jacobian  $J$  of  $f^{-1}$  decreases as we move away from  $v$  along a geodesic. From this, we can first deduce

**5.3.bis Lemma:** Let  $V$  be a Riemannian  $n$ -manifold satisfying  $\text{Ricci}(g) \geq -(n - 1)rg$ , where  $g$  is the metric and  $r$  a real number. Let  $v$  be a point of  $V$  and choose real numbers  $R \leq R'$ . Then

$$\frac{\text{vol}(B^V(v, R))}{\text{vol}(B^V(v, R'))} \geq \frac{\text{vol}(B^{V_r}(x, R))}{\text{vol}(B^{V_r}(x, R'))} = \frac{\int_0^R (\sinh(\sqrt{rt}))^{n-1} dt}{\int_0^{R'} (\sinh(\sqrt{rt}))^{n-1} dt}.$$

One interest of this lemma is that it holds even if one of (or both) the constants  $R, R'$  are greater than the injectivity radius at  $v$ . To see this, let  $U$  be the complement of the cut locus of  $V$ , let  $A$  (resp.  $A'$ ) be the subset of  $V_r$  that is the image under  $f$  of  $U \cap B^V(v, R)$  (resp.  $U \cap B^V(v, R')$ ).



With respect to the canonical measure  $d\mu$  of  $V_r$ , we have

$$\begin{aligned} \text{vol}(B^V(v, R)) &= \int_A J d\mu, & \text{vol}(B^{V_r}(x, R)) &= \int_{B^{V_r}(x, R)} d\mu, \\ \text{vol}(B^V(v, R')) &= \int_{A'} J d\mu, & \text{vol}(B^{V_r}(x, R')) &= \int_{B^{V_r}(x, R')} d\mu. \end{aligned}$$

Moreover, we can write

$$\text{vol}(B^V(v, R')) = \int_{B^{V_r}(x, R)} J d\mu, \quad \text{vol}(B^V(v, R')) = \int_{B^{V_r}(x, R')} J d\mu$$

simply by extending  $J$  to  $\hat{J}$  by zero! The function  $\hat{J}$  decreases along geodesics, as does  $J$ .

Now we consider polar coordinates  $(u, t) \in S \times \mathbb{R}_+$  based at  $x$ , where  $S = S_x V_r$  is the unit sphere of tangent vectors at  $x \in V_r$ . We then have  $d\mu = d\sigma \times d\nu$ , where  $\sigma$  is the canonical measure of  $S$  and  $d\nu$  is a measure on  $\mathbb{R}_+$  given by  $d\nu = (\sqrt{r})^{1-n} (\sinh(\sqrt{rt}))^{n-1}$ . We then have

$$\begin{aligned} \text{vol}(B^V(v, R)) &= \int_S \left( \int_0^R \hat{J}(u, t) d\nu \right) d\sigma, \\ \text{vol}(B^{V_r}(x, R)) &= \left( \int_S d\sigma \right) (\sqrt{r})^{1-n} \int_0^R (\sinh(\sqrt{rt}))^{n-1} dt \\ \text{vol}(B^V(v, R')) &= \int_S \left( \int_0^{R'} \hat{J}(u, t) d\nu \right) d\sigma, \\ \text{vol}(B^{V_r}(x, R')) &= \left( \int_S d\sigma \right) (\sqrt{r})^{1-n} \int_0^{R'} (\sinh(\sqrt{rt}))^{n-1} dt. \end{aligned}$$

However, the fact that  $J(u, t)$  decreases with respect to  $t$  implies that

$$\frac{\int_0^R \hat{J}(u, t) d\nu}{\int_0^R d\nu} \geq \frac{\int_0^{R'} \hat{J}(u, t) d\nu}{\int_0^{R'} d\nu},$$

proving the lemma.

**End of the proof of 5.3.** If  $v' \in V$  and  $\text{dist}(v, v') \leq R$ , then  $B(v, R) \subset B(v', 2R)$ , and so

$$\text{vol}(B^V(v', \varepsilon)) \geq \varphi_n(\varepsilon, R, r) \text{vol}(B^V(v', 2R)) \geq \varphi_n(\varepsilon, R, r) \text{vol}(B^V(v, R)),$$

and finally  $N(\varepsilon, R, V) \leq \varphi_n(\varepsilon, R, r)$ , where

$$\varphi_n(\varepsilon, R, r) = \frac{\int_0^R (\sinh(\sqrt{rn}))^{n-1} dt}{\int_0^\varepsilon (\sinh(\sqrt{rn}))^{n-1} dt}$$

depends only on  $(\varepsilon, R, r; n)$ .

**5.4. Remark:** The meaning of the preceding theorem is that the restriction

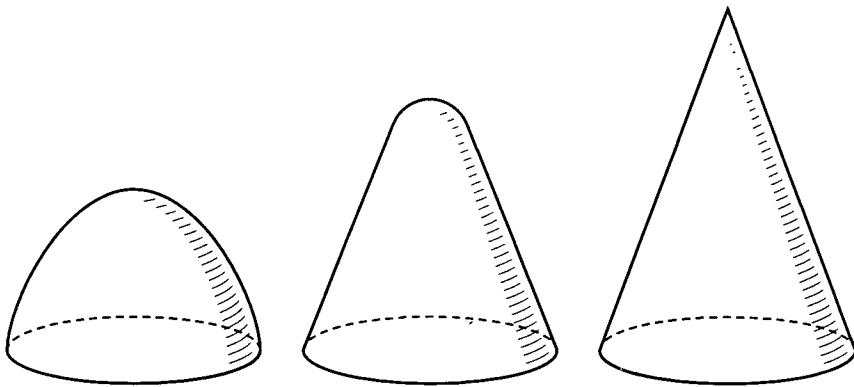
$$\text{Ricci}(g) \geq -(n-1)rg$$

permits only a finite number of geometries in the following sense: For each  $\varepsilon > 0$ , we can choose a finite number of model spaces  $X_i$  such that a ball of radius  $R$  in a such a manifold “resembles” the radius- $R$  ball in one of the  $X_i$  on the level of distances between points, up to  $\varepsilon$ .

If we considered manifolds that also satisfy  $\text{diam}(V, g) \leq d$ , we would have a precompact space for the usual Hausdorff distance, and we ask ourselves, How much do these conditions restrict the underlying topologies? We will proceed further in this direction at the end of the present chapter and in Chapter 8.

**5.5. Counterexamples:** Manifolds of dimension  $n$  having bounded Ricci curvature form a relatively compact (but not compact) space, i.e., a sequence of these manifolds can converge to a path metric space that is not an  $n$ -manifold. For example, let  $(e_1, e_2)$  be an orthonormal basis of the Euclidean plane,  $\Lambda_\varepsilon$  the lattice generated by the vectors  $e_1$  and  $\varepsilon e_2$ , and  $\mathbb{T}_\varepsilon$  the flat torus  $\mathbb{R}^2/\Lambda_\varepsilon$ . Then  $\text{Ricci}(\mathbb{T}_\varepsilon) = 0$  and the family  $\mathbb{T}_\varepsilon$  converges to the circle  $\mathbb{R}e_1/\mathbb{Z}e_1$  of lower dimension.

Even when the dimension remains the same, singularities may appear in the limit space: The surfaces  $C_\varepsilon$  of truncated cones in  $\mathbb{R}^3$ , equipped



with the induced length structures, converge to the cone, which is not a Riemannian manifold.

More is said about these two limit phenomena in Chapter 8.

For now, we mention the following applications of Proposition 5.2.

**5.6. Proposition:** *If  $X, Y$  are path metric spaces separated by a finite Hausdorff-Lipschitz distance, and if the family  $\{\lambda X : \lambda > 0\}$  is precompact, then the family  $\{\lambda Y : \lambda > 0\}$  is also precompact.*

**Proof.** By hypothesis, there exist two path metric spaces  $X_1, Y_1$  such that

$$d_H(X, X_1) = a < \infty, \quad d_L(X_1, Y_1) = b < \infty, \quad d_H(Y_1, Y) = c < \infty.$$

The net  $M'$  consisting of the centers of a maximal disjoint family of  $\varepsilon$ -balls in  $B^Y(y, R)$  induces a net in  $Y_1$ , then in  $X_1$ , and finally a net  $M$  in  $X$ , and the  $\varepsilon'_1$ -balls centered on  $M$  are disjoint in  $B^X(x, R'_1)$ , where  $\varepsilon'_\lambda = e^{-b}(\varepsilon - \lambda c) - \lambda a$  and  $R'_\lambda = e^b(R + \lambda c) + \lambda a$ , from which we can deduce that  $N(\varepsilon, R, Y) \leq N(\varepsilon'_1, R'_1, X)$ , and so, since the balls of  $\lambda X$  are  $\lambda$  times smaller than those of  $X$ ,  $N(\varepsilon, R, \lambda Y) \leq N(\varepsilon'_\lambda, R'_\lambda, \lambda X)$ . The second term is bounded (in  $\lambda$ ) by hypothesis, and so the  $N(\varepsilon, R, \lambda Y)$  are bounded.

**Application:** Let  $V$  be a compact manifold whose fundamental group is isomorphic to the discrete Heisenberg group, let  $Y$  be its universal cover, and let  $X$  be the continuous 3-dimensional Heisenberg group with its “Carnot” metric (see 1.1). Following Remark 2.23, the distance  $d_{HL}(X, Y)$  is finite. The spaces  $\lambda X$  are all identical and therefore form a precompact family, so that the same is true of the homotheties of  $Y$ . Thus, there exists a sequence  $\lambda_n \rightarrow 0$  such that the sequence  $\lambda_n Y$  Hausdorff converges to a complete, locally compact path metric space.

**5.7<sub>+</sub>.** The above can be reversed and used for a geometric proof of the *Mil-*

*nor conjecture* for groups of *polynomial growth* (defined in 5.9 below), which claims that these are *virtually nilpotent*, i.e., contain nilpotent subgroups of finite index.

**Exercise:** Let  $\Gamma$  have polynomial growth. Show that the family  $\{\varepsilon\Gamma : \varepsilon > 0\}$  is precompact. Study the Hausdorff limit  $H$  of  $\varepsilon_i\Gamma$  for some sequence  $\varepsilon_i \rightarrow 0$  and prove that it is a locally compact, finite-dimensional metric space with a transitive isometry group.

It follows via D. Montgomery's solution of Hilbert's fifth problem that  $H$  is *transitively* acted upon by a *connected Lie* group. Then one can show that  $\Gamma$  admits sufficiently many linear representations in order to apply

**Tits' freedom theorem:** *Every non-virtually solvable, finitely generated subgroup of  $GL_n(\mathbb{R})$  contains a free subgroup on two generators.*

This shows that our  $\Gamma$  is a virtually solvable, and by Bass' argument, a virtually nilpotent group (see [Gro]GPG for details).

**5.8+ Problem:** Is there an algebraic (or geometric) proof that avoids the limits? For example, one may try to develop a discrete version of the topological group techniques from [Mont-Zip].

**Exercise:** Prove directly that every group of polynomial growth of degree  $\leq 2$  is virtually abelian. (This is true by the above for degree  $< 4$ , but no direct argument is available, compare [Inc].)

## B. Growth of fundamental groups

In this section,  $\Gamma$  will denote a discrete group with a finite set  $\gamma_1, \dots, \gamma_p$  of generators,  $B(R)$  will be the ball of radius  $R$  with respect to the algebraic norm associated with this system (i.e., the set of elements of  $\Gamma$  that can be represented by a word having length less than  $R$  in this set), and  $N(R)$  will denote the number of elements in  $B(R)$ .

**5.9. Definition:** The group  $\Gamma$  is said to have *polynomial growth* if there exists a real  $p$  such that  $N(R) \leq R^p$  for sufficiently large  $R$ . If there is a  $c > 0$  such that  $N(R) \geq e^{cR}$  for large  $R$ , then  $\Gamma$  is said to have *exponential growth*.

**5.10. Proposition:** *The growth type is invariant under quasi-isometries.*

**Proof.** For a net  $M$  in a metric space  $X$ , we denote by  $N(M, R)$  the number of points of  $M$  in the ball of radius  $R$  centered at  $x$ . Let  $\Gamma_1, \Gamma_2$  be two

quasi-isometric groups, so that there exist two compact manifolds  $V_1, V_2$  with fundamental groups  $\Gamma_1, \Gamma_2$ , respectively, and metric spaces  $X_1, X_2$  such that

$$d_H(\tilde{V}_1, X_1) = \rho_1 < \infty, \quad d_L(X_1, X_2) = b < \infty, \quad d_H(X_2, \tilde{V}_2) = \rho_2 < \infty.$$

These spaces are pointed at  $\tilde{v}_1, x_1, x_2, \tilde{v}_2$ . Let  $M_1, M_2$  be the nets  $\Gamma_1 \tilde{v}_1, \Gamma_2 \tilde{v}_2$ . If  $d_1$  is the diameter of  $V_1$ , then  $M_1$  is a  $d_1$ -net of  $\tilde{V}_1$ . Since the algebraic and geometric norms on  $\Gamma_1$  are equivalent (see Proposition 3.22), it follows that for some constant  $a$ , we have  $N(M_1, R) \leq N_1(aR)$  ( $= N(R)$  of  $\Gamma_1$ ). By the usual procedure, we associate with each point of  $M_1$  a point of  $X_1$  in order to obtain a  $(d_1 + 2\rho_1)$ -net  $M'_1$  of  $X_1$ , such that  $N(M'_1, R) \leq N_1(aR + \rho_1)$ . There exists a homeomorphism of  $X_1$  onto  $X_2$  having dilatation less than  $e^b$ ; the image of  $M'_1$  is a  $e^b(d_1 + 2\rho_1)$ -net  $M'_2$  of  $X_2$  such that  $N(M'_2, R) \leq N(e^b(aR + \rho_1))$ . Since  $d_H(X_2, V_2) \leq \rho_2$ , we have transformed the net  $M'_2$  into a  $(e^b(d_1 + 2\rho_1) + 2\rho_2)$ -net  $M''_2$  in  $\tilde{V}_2$  such that  $N(M''_2, R) \leq N_1(e^b(aR + \rho_1) + \rho_2)$ .

We now have two nets  $M_2, M''_2$  of  $\tilde{V}_2$ , and we will show that their respective densities are comparable. Set  $\delta = e^b(d_1 + 2\rho_1) + 2\rho_2$  and note that the number of elements of  $M_2$  contained in any  $\delta$ -ball is bounded (by a real number  $K$ ) since  $\Gamma_2$  acts by isometries. For each  $x \in (M_2)^R = M_2 \cap B^{V_2}(v_2, R)$ , we choose a  $y = f(x) \in (M''_2)^{R+\delta}$  such that  $d(x, y) \leq \delta$ , which is possible since  $M''_2$  is a  $\delta$ -net. Then, each fiber of the map  $f: M_2^R \rightarrow (M''_2)^{R+\delta}$  has at most  $K$  points, which implies that

$$N_2(R) = \text{card}(M_2^R) \leq K N(M''_2, R + \delta) \leq K N_1(e^b(aR + \rho_1) + \rho_2). \quad (*)$$

For the polynomial case of the assertion, we set

$$p_i = \inf\{p \in \mathbb{R} : N_i(R) \leq R^p \text{ for sufficiently large } R\}.$$

The assumption that  $\Gamma_1$  has polynomial growth means that  $p_1$  is finite, but it follows from the inequality  $(*)$  that for each  $p > p_1$ , we then have  $N_2(R) \leq R^p$  for sufficiently large  $R$ , and so  $p_2 \leq p_1$ . Of course, by symmetry we can conclude that  $p_1 = p_2$ , and so both are simultaneously finite.

For the exponential case, we deduce from  $(*)$  that

$$N_1(R) \leq \frac{1}{K} N_2 \left( e^{-b} \left( \frac{R - \delta}{a} - \rho_1 \right) - \rho_2 \right).$$

If  $\Gamma_2$  has exponential growth, then there exists  $c > 0$  such that, for sufficiently large  $R$ , we have  $N_2(R) \leq e^{cR}$ , which implies that for  $c' < c$  and large  $R$ ,  $N_1(R) \leq \exp(c'e^{-b}a^{-1}R)$ . Thus,  $\Gamma_1$  has exponential growth.

This proof leads to the conclusion that

$$\liminf_{R \rightarrow \infty} \frac{\log(N(R))}{\log(R)}$$

is invariant of quasi-isometry, which gives meaning to the expression “*polynomial growth of degree p.*” On the other hand,

$$\liminf_{R \rightarrow \infty} \frac{\log(N(R))}{R}$$

is not invariant, which justifies the following definition.

**5.11. Definition:** The *entropy* of a set  $\{\gamma_i\}$  of generators is the number

$$h(\{\gamma_i\}) = \liminf_{R \rightarrow \infty} \frac{\log(N(R))}{R},$$

and the *entropy of the group*  $\Gamma$ , denoted  $h(\Gamma)$ , is the infimum of the entropies of all sets of generators.

**5.12. Remark:** If  $h(\Gamma)$  is strictly positive, then  $\Gamma$  has exponential growth. On first sight, however, there seems to be no reason for the converse to be true. Nevertheless, we do not know of a counterexample.<sup>1</sup>

**5.13. Example:** For the free group  $\Gamma$  on  $k$  generators,  $h(\Gamma) = \log(2k - 1)$ .

Indeed, if  $\gamma_1, \dots, \gamma_k$  are independent generators, then  $N(R)$  is exactly the number of words of length less than  $R$ . But in order to create a word of length  $R$ , it is necessary to choose the first letter among one of the  $2k$  letters  $\gamma_i, \gamma_i^{-1}$ , then to choose among the  $(2k - 1)$  letters for the second, etc., and so

$$N(R) = N(R - 1) + 2k(2k - 1)^{R-1} = \frac{2k}{2k - 2}(2k - 1)^R$$

and  $h\{\gamma_i\} = \log(2k - 1)$ . If  $\beta_1, \dots, \beta_n$  is another set of generators, we select  $k$  independent generators  $\beta_{i_1}, \dots, \beta_{i_k}$ . The minimal length of an element of  $\Gamma$  as a function of the  $\beta_{i_j}$  is larger than for  $\beta_1, \dots, \beta_n$ , from which we conclude that  $h\{\beta_i\} \geq \log(2k - 1)$ .

**5.14. Conjecture:** If  $\Gamma$  is a discrete group with  $k$  generators and  $p$  relations, then  $h(\Gamma) \geq \log(2(k - p) - 1)$ .

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<sup>1</sup>I have recently received a preprint discussing this subject matter, but to my shame I have lost it. My apologies to the author.

We have been able to resolve this question in several cases by exhibiting free subgroups. If  $p = 1$ , then the conjecture follows from the “Freiheit” theorem of Magnus (see [Lynd–Sch]). Stallings [Stall] has shown that, if  $p \leq k - 2$ , and if there is an integer  $q$  such that  $H_4(\Gamma, \mathbb{Z}/q\mathbb{Z}) = \Gamma/[\Gamma, \Gamma] \oplus \mathbb{Z}/q\mathbb{Z}$  has rank  $k - p$ , then the conjecture is true. Finally, we have in general

$$h(\Gamma) \geq \text{const} \log(2(k - p) - 1),$$

which can be seen by looking at some subfactor group of  $\Gamma$  (see [Bau–Pri] and p. 83 in [Gro]<sub>VBC</sub>).

**Remark<sub>+</sub>:** It is known that the entropy of the *generators*  $\gamma_1, \dots, \gamma_k$  is at least  $\log(2(k - p) - 1)$ . Moreover, by a theorem of N. S. Romanovski (see [Rom]), *there are  $k - p$  generators among the  $\gamma_i$  which are freely independent.*

For the universal cover of a compact Riemannian manifold, we will relate the growth of balls with the growth of the fundamental group.

**5.15. Definition:** The *entropy* of a compact Riemannian manifold  $V$  is the number

$$h(V) = \liminf_{R \rightarrow \infty} \frac{\log(\text{vol}(B^{\tilde{V}}(\tilde{v}, R)))}{R}.$$

**Remark:** This number is independent of the base point  $\tilde{v} \in \tilde{V}$ . Indeed, if  $\tilde{v}, \tilde{v}' \in \tilde{V}$ , then  $B^{\tilde{V}}(\tilde{v}', R) \subset B^{\tilde{V}}(\tilde{v}', R + \delta)$ , where  $\delta = d(\tilde{v}, \tilde{v}')$ , and so for each  $c > h(V, \tilde{v})$  and sufficiently large  $R$ ,

$$\frac{\log(\text{vol } B(v', R))}{R} \leq c + \frac{\delta}{R}.$$

Thus,  $h(V, \tilde{v}') \leq c$  and finally  $h(V, \tilde{v}') \leq h(V, \tilde{v})$ .

**Remark:** In [Din] and [Mann], it is shown that the topological entropy of the geodesic flow on the unit tangent bundle of a manifold  $V$  is bounded below by  $h(\pi_1(V))$ , which justifies the use of the term *entropy* for this invariant group as well as the number related to the volume of balls.

**5.16. Theorem (cf. [Šva] and [Milnor]<sub>CFG</sub>):** *If  $V$  is a compact manifold of diameter  $d$ , then  $h(V) \leq 2d h(\pi_1(V))$ .*

**Proof.** There exists an  $\varepsilon > 0$  such that every closed curve in  $V$  of length  $< 2\varepsilon$  is homotopic to 0. Thus, each element of  $\Gamma = \pi_1(V)$  has geometric norm greater than  $\varepsilon$  (except the identity), which implies that the balls  $B^{\tilde{V}}(\gamma\tilde{v}, \varepsilon/2)$  of radius  $\varepsilon/2$  centered at points of the orbit  $\Gamma\tilde{v}$  are disjoint. Let  $\tau$  be the common volume of these small balls; the number  $N'(R)$  of

elements of  $\Gamma\tilde{v}$  lying within the ball of center  $\tilde{v}$  and radius  $R$  is then bounded above by  $\tau^{-1} \text{vol}(B^{\tilde{V}}(\tilde{v}, R))$ , and consequently,

$$h(V) = \liminf_{R \rightarrow \infty} \frac{\log(\text{vol } B^{\tilde{V}}(\tilde{v}, R))}{R} \geq \liminf_{R \rightarrow \infty} \frac{N'(R)}{R}.$$

However, we proved (Proposition 3.22) the inequality  $\|\cdot\|_{geo} \leq K\|\cdot\|_{alg}$ , where  $K$  is the largest geometric norm of a generator, which can be less than  $2d$  for an appropriately chosen set of generators. Thus,

$$N(R) = \text{card}\{\gamma \in \Gamma : \|\gamma\|_{alg} \leq R\} \leq N'(2dR),$$

and so

$$h(\Gamma) \leq 2d \liminf_{R \rightarrow \infty} \frac{N'(2dR)}{2dR},$$

i.e.,  $h(\Gamma) \leq 2dh(V)$ .

**5.17. Application:** Suppose that a compact Riemannian manifold  $(V, g)$  satisfies  $\text{Ricci}(g) \geq -(n-1)rg$  for a constant  $r > 0$ . Then, by Bishop's inequality (see 5.3) the balls in  $\tilde{V}$  grow more slowly than in the simply connected hyperbolic space that satisfies the inequality  $\text{Ricci} = -(n-1)rg$ , i.e.,

$$\text{vol}(B^{\tilde{V}}(\tilde{v}, R)) \leq \text{const} \int_0^R \left( \frac{\sinh(\sqrt{rt})}{\sqrt{r}} \right)^{n-1} dt \leq \text{const } e^{\sqrt{rt}},$$

and so  $h(V) \leq \sqrt{r}$ . Using the theorem, we can conclude that the entropy of the fundamental group of  $V$  is necessarily less than  $\sqrt{r}/2d$ . In particular, if  $\pi_1(V)$  is free, it has at most  $(\exp(\sqrt{r}/2d) + 1)/2$  generators.

In this connection, we observe that sometimes the hypothesis  $\text{Ricci}(g) \geq -(n-1)rg$  enables us to bound the growth of balls from below as well as from above (cf. [Yau]<sub>ICFE</sub>).

**5.18. Proposition:** *If  $V$  is a complete, noncompact Riemannian manifold with nonnegative Ricci curvature, then for each  $\alpha < 1$ , there exists a  $c_\alpha > 0$  such that  $\text{vol}(B^V(v, R)) \geq c_\alpha R^\alpha$  for large  $R \rightarrow \infty$ .*

**Proof.** For each  $v \in V$  and  $R, R'$ , Remark 5.3 implies that

$$\frac{\text{vol}(B^V(v, R))}{\text{vol}(B^V(v, R'))} \leq \frac{R^n}{(R')^n}.$$

Choose a point  $v \in V$ . Then for each  $t > 0$ , there is a point  $x \in V$  lying at exactly distance  $t$  from  $v$ . Indeed, since  $V$  is a complete, locally

compact, noncompact path metric space,  $V$  is not bounded (by the Hopf–Rinow theorem 1.10); thus, there exists a point  $y \in V$  such that  $d(v, y \geq t)$ , and if  $\gamma$  is a path connecting  $v$  to  $y$ , the continuous function  $s \mapsto d(v, \gamma(s))$  assumes the value  $t$ .

Given  $\alpha < 1$ , fix  $b \in (1, \alpha^{-1})$  and set  $r_i = 2^{b^i}$ ,  $R_i = \sum_{j=0}^i 2r_j$ . Choose a point  $x_i$  at a distance  $r_i + R_{i-1}$  from  $v$ ; by construction, the balls  $B(x_i, r_i)$  are disjoint and  $\bigcup_{j=0}^i B(x_j, r_j) \subset B(x_i, r_i + R_{i-1})$ . If we set  $\tau_i = \sum_{j=0}^i \text{vol}(B(x_j, r_j))$ , then  $\tau_i \leq \text{vol}(B(x_i, r_i + R_{i-1}))$  and

$$\frac{\tau_i}{\tau_i - \tau_{i-1}} \leq \left( \frac{R_i + R_{i-1}}{r_i} \right)^n,$$

so that  $\tau_i \geq (1 - (1 + R_{i-1}/r_i)^{-n})^{-1} \tau_{i-1}$ . Note that for each  $i$ ,

$$R_{i-1} = 2 \sum_{j=0}^{i-1} 2^{b^j} \leq 2 \sum_{j=0}^{i-1} 2^{[b^j]+1} \leq 2 \sum_{0 \leq k \leq [b^{i-1}]+1} 2^k \leq 2 \cdot 2^{b^{i-1}+2},$$

and so  $R_{i-1}/r_i \rightarrow 0$  as  $i \rightarrow \infty$ . Moreover,  $R_{i-1} = 2r_{i-1} + R_{i-2}$ , and so  $R_{i-1} \sim 2r_{i-1}$  as  $i \rightarrow \infty$ . It follows that, for sufficiently large  $i$ ,  $1 - (1 + R_{i-1}/r_i)^{-n} \geq 3n(r_{i-1}/r_i)$  and so  $\tau_i/\tau_{i-1} \leq r_i/3nr_{i-1}$ . However,  $r_i/r_{i-1} = (r_{i+1}/r_i)^{1/b}$ ; since  $1/b \geq \alpha$ , it follows that for sufficiently large  $i$ ,

$$\frac{1}{3n} \left( \frac{r_{i+1}}{r_i} \right)^{1/b} \geq \left( \frac{r_{i+1}}{r_i} \right)^\alpha,$$

and so  $\tau_i r_{i+1}^{-\alpha} \geq \tau_{i-1} r_i^{-\alpha}$ , and  $\tau_i \geq \text{const}(r_{i+1})^\alpha$ . Since  $\bigcup_{j=0}^i B(x_j, r_j) \subset B(v, r_i + R_{i-1})$ , it follows that  $\text{vol}(B(v, R_i)) \geq \text{const } r_{i+1}^\alpha \geq \text{const}' R_{i+1}^\alpha$  for sufficiently large  $i$ , since  $R_i \sim 2r_i$  as  $i \rightarrow \infty$ .

To conclude the proof, we note that if  $R$  is sufficiently large, then there is an  $i$  such that  $R_i \leq R \leq R_{i+1}$  and so

$$\text{vol}(B(v, R)) \geq \text{vol}(B(v, R_i)) \geq \text{const } R_{i+1}^\alpha \geq \text{const } R^\alpha.$$

## C. The first Betti number

In the preceding section, we found an upper bound for the number of generators of a fundamental group, provided that it is free. We will now generalize this result by refining the technique used in Section 5.17 and by finding an upper bound for the first Betti number in terms of the diameter and Ricci curvature of a manifold.

**5.19. Lemma:** *Let  $X$  be a compact path metric space of diameter  $d$  and having a universal cover  $\tilde{X}$ . Then for each point  $\tilde{x} \in \tilde{X}$  and each  $\varepsilon > 0$ ,*

there is a finite covering  $X' \rightarrow X$  and set of generators  $\gamma_1, \dots, \gamma_k$  for the deck transformation (Galois) group of  $X'$  such that

$$\text{I. } d(\tilde{x}, \gamma_i \tilde{x}) \leq 2d + \varepsilon \quad \text{and} \quad \text{II. } d(\gamma_i \tilde{x}, \gamma_j \tilde{x}) \geq \varepsilon$$

if  $i \neq j$ .

**Proof.** Consider the families  $\{\gamma_i\}$  of elements of  $\pi_1(X)$  that satisfy the properties I)  $\|\gamma_i\|_{geo} \leq 2d + \varepsilon$  and II) if  $i \neq j$ ; then  $\|\gamma_i \gamma_j^{-1}\|_{geo} \geq \varepsilon$ . Such families exist (e.g., the family  $\{e\}$ ), so that we can choose one having the maximal number  $p$  of elements and denote by  $\Gamma'$  the normal subgroup of  $\pi_1(X)$  that it generates. With this group is associated a covering space  $X'$  of  $X$ , defined as the quotient of  $\tilde{X}$  by the action of  $\Gamma'$ , whose automorphism group is isomorphic to  $\pi_1(X)/\Gamma'$ . Let  $x'$  denote the projection of  $\tilde{x}$  into  $X'$  and suppose that there exists  $z' \in X'$  such that  $\text{dist}(x', z') > d + \varepsilon$ . If  $\tilde{z}$  lies in the fiber over  $z'$ , then there exists  $\alpha \in \pi_1(X)$  such that  $\text{dist}(\tilde{z}, \alpha \tilde{z}) \leq d$ , and so  $\text{dist}(z', \alpha x') \leq d$ , which implies that  $\varepsilon < \text{dist}(x', \alpha x') < 2d + \varepsilon$ , and so 1) there exists  $\gamma'_0 \in \Gamma'$  such that  $\text{dist}(\gamma'_0 \tilde{x}, \alpha \tilde{x}) \leq 2d + \varepsilon$ , i.e.,  $\|(\gamma'_0)^{-1} \alpha\|_{geo} \leq 2d + \varepsilon$ , and 2) for each  $\gamma' \in \Gamma'$ ,  $\text{dist}(\gamma' \gamma'_0 \tilde{x}, \alpha \tilde{x}) > \varepsilon$ , i.e.,  $\|(\gamma')^{-1} (\gamma'_0)^{-1} \alpha\|_{geo} > \varepsilon$ . The system  $\gamma_1, \dots, \gamma_k, (\gamma'_0)^{-1} \alpha$  still satisfies conditions 1) and 2), which contradicts the maximality of the  $\gamma_i$ . We conclude that each point of  $X'$  lies at a distance less than  $d + \varepsilon$  from  $x'$ , and so  $X'$  is compact with diameter less than  $2d + 2\varepsilon$ . In particular,  $\Gamma'$  has finite index in  $\pi_1(X)$ .

**5.20. Corollary:** By Hurewicz's theorem (see [Span], p. 148), the quotient of  $\pi_1(X)$  by its commutator subgroup is isomorphic to  $H_1(X; \mathbb{Z})$ . In particular, if the elements  $\gamma_1, \dots, \gamma_p$  of  $\pi_1(X)$  generate a normal subgroup of finite index in  $\pi_1(X)$ , then their images in  $H_1(X; \mathbb{R})$  generate all of  $H_1(X; \mathbb{R})$ . In other words,  $b_1 = \dim(H_1(X; \mathbb{R})) \leq p$ . However, property II) of the system  $\gamma_i$  implies that the balls  $B^{\tilde{X}}(\gamma_i \tilde{x}, \varepsilon/2)$  are disjoint, while property I) implies that they are all contained in  $B^{\tilde{X}}(\tilde{x}, 2d + 3\varepsilon/2)$ . If  $X$  is a Riemannian manifold that satisfies the identity  $\text{Ricci}(g) \geq -(n-1)rg$ , then the inequality of Theorem 5.3 gives

$$\begin{aligned} b_1 \leq p &\leq \frac{\text{vol}(B(\tilde{x}, 2d + 3\varepsilon/2))}{\text{vol}(B(\tilde{x}, \varepsilon/2))} \\ &\leq \int_0^{5d} (\sinh(\sqrt{rt}))^{n-1} dt \left( \int_0^d (\sinh(\sqrt{rt}))^{n-1} dt \right)^{-1}, \end{aligned}$$

where  $\varepsilon$  is a function of  $n, r, d$  only.

**5.21. Theorem:** *There is an integer-valued function  $\varphi(n, r, d)$  such that for each Riemannian  $n$ -manifold  $(V, g)$  of diameter  $d$  and Ricci curvature*

$\text{Ricci}(g) \geq -(n-1)rg$ , the first Betti number of  $V$  satisfies the inequality  $b_1 \leq \varphi(n, r, d)$ . Moreover, when  $rd^2$  is sufficiently small, the function  $\varphi$  equals  $n$ .

**Proof.** The preceding corollary shows that the function

$$\varphi(n, r, d) = \sup b_1(V; \mathbb{R})$$

is finite provided that  $V$  is a Riemannian  $n$ -manifold with diameter  $d$  and  $\text{Ricci}(g) \geq -(n-1)rg$ . It remains to prove the second assertion.

By the case  $\varepsilon = 0$  of Lemma 5.19, there exist  $p$  elements of  $\pi_1(V)$  and a point  $\tilde{x}$  of  $\hat{V}$  such that  $\|\gamma_i\|_{geo} \leq 2d$ , and such that the subgroup  $\Gamma'$  generated by the  $\gamma_i$  has finite index in  $\pi_1(V)$ . Let  $h$  denote the natural homomorphism from  $\pi_1(V)$  into  $H_1(V; \mathbb{R})$ ; then  $h(\Gamma')$  generates the vector space  $H_1(V; \mathbb{R})$ .

We first extract a subgroup  $\Gamma'' \subset \Gamma'$  whose image under  $h$  still generates  $H_1(V; \mathbb{R})$ , all of whose elements have norm  $\geq d$ . To begin, we extract a basis of  $H_1$  from the vectors  $h(\gamma_i)$ , which we denote by  $h(\gamma_1), \dots, h(\gamma_k)$ , and restrict our attention to the subgroup  $\Gamma'$  generated by  $\gamma_1, \dots, \gamma_k$ . Note that only finitely many elements of  $\Gamma'$  have norm less than  $d$ . If  $\gamma$  and each of its powers have norm less than  $d$ , then  $\gamma$  has finite order, and so  $h(\gamma) = 0$ , i.e.,  $\gamma = 1$ , since  $h$  is injective by construction of the family  $\gamma_1, \dots, \gamma_k$ . Consequently, there is a power of  $\gamma$  having norm greater than  $d$ , and thus an integer  $m$  such that  $d \leq \|\gamma^m\|_{geo} < 2d$ . Choose a generator  $\gamma_j$  such that  $h(\gamma)$  has a nonzero  $j$ -th component in the basis  $h(\gamma_1), \dots, h(\gamma_k)$ , and replace  $\gamma_j$  with  $\gamma'_j = \gamma^m$  in the generating set. The new group no longer contains  $\gamma$  (if it did, then a nontrivial linear combination of the  $k-1$  vectors  $\gamma_i$   $i \neq j$  would be zero). After a finite number of operations, we obtain the desired group: it is free abelian with  $b_1$  generators of norm less than  $2d$ , and all of its elements have geometric norm  $\geq d$ .

The number of points in the orbit  $\Gamma''\tilde{x}$  lying within the ball  $B^{\hat{V}}(\tilde{x}, 2pd)$  is at least equal to the number of points  $(\lambda_i) \in \mathbb{Z}^{b_1}$  such that  $\sum_{i=1}^{b_1} |\lambda_i| \leq p$ , i.e., approximately  $(1/2)(2\pi)^{b_1}/b_1!$ . By construction, however, the balls  $B^{\hat{V}}(\gamma\tilde{x}, 1/2d)$  are disjoint and lie within  $B^{\hat{V}}(\tilde{x}, 2pd)$ , and their number is at most

$$\frac{\text{vol}(B(x, 2pd))}{\text{vol}(B(x, 1/2d))} \leq \int_0^{2pd\sqrt{r}} (\sinh(t))^{n-1} dt \left( \int_0^{1/2d\sqrt{r}} (\sinh(t))^{n-1} dt \right)^{-1},$$

which tends to  $(4p)^n$  as  $rd^2 \rightarrow 0$ , implying that  $b_1 \leq n$ . More precisely, suppose that  $b_1 > n$ . If  $c$  is a real number  $< 1$ , then there exists  $p_0$  such that the number of points of  $\Gamma''\tilde{x}$  within  $B(\tilde{x}, 2p_0d)$  will be  $\geq c(2p_0)^{b_1}/b_1!**$

and  $p_0^{b_1-n} > 4^n b_1! c^{3-2n} 2^{1-b_1}$ . There exists a  $\varepsilon > 0$  such that for  $|t| \leq \varepsilon$ , we have  $c \leq (\sinh(t))/t \leq (1/c)$ . So, for  $rd^2 \leq \varepsilon^2/4p_0^2$ , the ratio of the integrals is less than  $c^{2-2n}(4p_0)^n$ , which implies that  $p_0^{b_1-n} \leq 4^n b_1! c^{3-2n} 2^{1-b_1}$ , a contradiction. Finally, we note that the bound  $\varepsilon_n$  such that  $rd^2 \leq \varepsilon_n$  implies  $b_1 \leq n$  decreases exponentially with  $n$ .

**Example:** The  $n$ -torus satisfies  $b_1 = n$  and admits metrics with zero Ricci curvature, namely all the flat metrics.

**5.22. Remark:** From [Gro]<sub>AFM</sub>, we can deduce the following more precise result: If the diameter and the sectional curvature of  $V$  are sufficiently close to 0, and if  $b_1 = n$ , then a finite covering of  $V$  is diffeomorphic to a torus.

*Conjecture:* If  $d\sqrt{r}$  is sufficiently small, and if  $b_1 = n$  (or even if only  $b_1 \geq n - 1$ ), then  $V$  is homeomorphic to a torus. (For  $b_1 = n$ , this has been proved by T. Colding, and for  $b_1 = n - 1$  disproven by Anderson, see [And] and [Col]<sub>LMPR</sub>.)

Our argument is specific for the first Betti number over the reals but not over a finite field. This suggests that the analytical methods of Bochner could yield the same result.

Bochner introduced, for each  $k = 1, \dots, n$ , a quadratic form  $R_k$  on the exterior power  $\Lambda^k TV$  such that  $R_1$  coincides with the Ricci curvature. He showed that (see [Boch–Yano]), if  $R_k$  is everywhere positive, then

$$b_k = \dim(H^k(V; \mathbb{R})) \leq \frac{n!}{(n-k)!k!}.$$

For a Riemannian manifold such that  $R_k \geq -r_k g^{(k)}$ , where  $g^{(k)}$  denotes the  $k$ -th exterior power of the metric  $g$ , the Bochner formula show that the number of eigenvalues  $\leq \lambda$  of the Hodge Laplacian on  $k$ -forms is bounded by the corresponding number for the *Bochner Laplacian* shifted by  $r_k$ ,

$$N(\Delta_{\text{Hodge}}, \lambda) \leq N(\Delta_{\text{Bochner}}, \lambda + r_k)$$

for all  $\lambda \geq 0$ . Since the latter number allows a bound in terms of the Laplacian on functions via Kato's inequality (see 3 $\frac{1}{2}$ .62), our result in Appendix C<sub>+</sub> implies that for each  $k$ ,

$$b_k = N(\Delta_{\text{Hodge}}, 0) \leq (d/\sqrt{r_k})^n c_n^{1+d\sqrt{r}} + \frac{n!}{(n-k)!k!}.$$

For other results following from the Bochner formula, see [Gal]<sub>IIA</sub>.

## D. Small loops

In the first section of this chapter, it became apparent that Riemannian manifolds with bounded (above) diameter and bounded (below) Ricci curvature fall into a finite number of collections of manifolds having closely related geometric properties. We then promised some results addressing the topology of these manifolds. This is the topic of the present section.

**5.23. Definition:** For any positive constant  $c$ , we denote by  $\mathcal{G}_c$  the family of groups  $\Gamma$  of finite type satisfying the following properties:

1.  $\Gamma$  is torsion-free.
2. Each  $\gamma \in \Gamma$  is contained in a unique maximal cyclic subgroup  $Z_\gamma$ , and  $Z_\gamma \neq \Gamma$ .
3. If  $\gamma$  and  $\delta$  generate a noncyclic subgroup of  $\Gamma$ , then this subgroup has exponentially growth and entropy  $c$  with respect to the generating set  $\{\gamma, \delta\}$  (see Definition 5.11).

**Remark:** By (2) and (3), each element of  $\mathcal{G}_c$  has trivial center. If  $c \leq \log(3)$ , then the class  $\mathcal{G}_c$  contains the free noncyclic groups and the fundamental groups of manifolds of negative curvature (see Remarks 6.10(2) and 6.12). This definition enables us to give a new version of *Margulis' lemma* (compare [Gro]AFM, p. 240, and see Remark 8.50).

**5.24. Theorem:** Let  $(V, g)$  be a compact Riemannian manifold such that  $\text{Ricci}(g) \geq -(n - 1)rg$ . If the group  $\pi_1(V)$  is in the family  $\mathcal{G}_c$ , then there exists a point  $\tilde{v} \in \tilde{V}$  such that, for each nontrivial  $\gamma \in \pi_1(V)$ , we have  $\text{dist}(\tilde{v}, \gamma\tilde{v}) \geq c/\sqrt{r}$ .

The proof relies on the following two lemmas.

**5.25. Lemma:** Let  $\Gamma$  be a group satisfying properties (1) and (2) of Definition 5.23 above. Then each element of  $\Gamma$  has at most one square root.

**Proof.** Elementary.

**5.26. Lemma:** Let  $X$  be a compact, connected manifold. Let  $\Gamma^{\min(x)}$  be the subgroup of  $\pi_1(X, x)$  generated by those elements whose distance to the identity is minimal (with respect to the geometric norm 3.20). In other words,  $\Gamma^{\min(x)}$  is generated by nontrivial geodesic loops based at  $x$  having minimal length. If  $\pi_1$  satisfies properties (1) and (2), and if for each  $x$  the

group  $\Gamma^{min(x)}$  is cyclic, then for each  $x$  this group is contained in the center of  $\pi_1(X, x)$ .

**Proof.** Since for each curve  $u$  joining the two points  $x, y$  and for each  $\gamma \in \pi_1(X, x)$ , we have

$$|\|u^{-1}\gamma u\|_y - \|x\|_x| \leq 2 \text{length}(u),$$

the discrete and closed set (cf. 1.13) of lengths of closed, nontrivial geodesics based at  $x$  varies continuously with  $x$ . If  $x, y$  are sufficiently close and joined by a minimizing geodesic  $u$ , there exists  $\gamma \in \pi_1(X, x)$ , based at a closed minimizing geodesic at  $x$ , such that  $u^{-1}\gamma u$  yields a closed minimizing geodesic at  $y$ . In other words,  $u^{-1}\Gamma^{min(x)}u \cap \Gamma^{min(y)} \neq \{e\}$ , thus  $u^{-1}Z^x u = Z^y$  for the maximal cyclic subgroups  $Z^x, Z^y$  corresponding to the generators of  $\Gamma^{min(x)}, \Gamma^{min(y)}$ .

Now let  $\delta$  be an element of  $\pi_1(X, x)$  represented by a closed geodesic loop based at  $x$ . By applying the argument above to smaller and smaller subdivisions of this loop, we obtain  $\delta^{-1}Z^x\delta = Z^x$ . If  $\alpha$  is a generator of  $Z^x$ , then  $\delta^{-1}\alpha\delta$  is also, thus  $\delta^{-1}\alpha\delta = \alpha^{\pm 1}$ , the group being torsion-free. But if  $\delta^{-1}\alpha\delta = \alpha^{-1}$ , then  $\delta = \alpha\delta\alpha$ , and  $\delta^2 = (\alpha\delta)^2$ , contrary to the preceding lemma. The inner automorphism  $\gamma \mapsto \delta^{-1}\gamma\delta$  therefore leaves  $Z^x$  pointwise invariant.

**Proof of the theorem.** Since  $\pi_1$  has trivial center, Lemma 5.26 guarantees the existence of a point  $a \in V$  and two elements  $\gamma, \delta \in \pi_1(V, a)$  represented by minimal geodesic loops of length  $\varepsilon$  based at  $a$  and generating a noncyclic group  $\Gamma$ .

Since the loops have the same length, we will easily be able to compute the number  $N(p)$  of points in the universal cover  $(\tilde{V}, \tilde{a})$  of  $(V, a)$  belonging to  $B(\tilde{a}, p\varepsilon) \cap \Gamma\tilde{a}$ .

There are at least as many elements of  $\Gamma$  that can be written as words in  $\gamma, \delta$  and their inverses that have length less than or equal to  $p$ . By property (3) of  $\pi_1$ , we have  $N(p) \geq e^{cp}$ .

There are at most  $\text{vol}(B(\tilde{a}, p\varepsilon)) / \text{vol}(B(\tilde{a}, \varepsilon))$ , and the hypothesis for the Ricci curvature enables us to apply Bishop's inequality (cf. 5.3.bis)

$$\frac{\text{vol}(B^V(\tilde{a}, p\varepsilon))}{\text{vol}(B^V(\tilde{a}, \varepsilon))} \leq \int_0^{p\varepsilon} (\sinh(\sqrt{rt}))^{n-1} dt \left( \int_0^\varepsilon (\sinh(\sqrt{rt}))^{n-1} dt \right)^{-1},$$

the ratio of the volumes of balls of radii  $p\varepsilon$  and  $\varepsilon$  in hyperbolic space whose Ricci curvature satisfies  $\text{Ricci}(g) = -(n-1)rg$ . As  $p \rightarrow \infty$ , the ratio is on the order of  $\exp(\sqrt{rp\varepsilon})$ . All of the above implies for large  $p$  inequalities of the form  $e^{cp} \leq N(p) \leq f(n, r, \varepsilon)e^{\sqrt{rp\varepsilon}}$ , which are possible only if  $\varepsilon \geq c/\sqrt{r}$ .

**5.26.bis Remark:** (a) By [Gro]<sub>GPG</sub>, we can replace condition (3) of Definition 5.23 by

(3)'  $\Gamma$  has no subgroup isomorphic to  $\mathbb{Z} \oplus \mathbb{Z}$ .

The conclusion of Theorem 5.24 then becomes  $d(\tilde{v}, \gamma\tilde{v}) \geq c_n/\sqrt{r}$  for a universal constant  $c_n$  (see 5.32).

( $b_+$ ) The proof above makes essential use of a continuity argument (following in the steps of the original approach by Kazhdan–Margulis, see [Kaz–Marg] and [Ragun]), since we produce a pair of independent short loops of equal length at some point in  $V$  by bringing together the shortest loops from different points. This idea extends to  $k$ -parametric families of loops for all  $k \geq 1$  and yields  $(k+1)$ -tuples of “independent” loops at certain points in  $V$  under suitable topological assumptions (see 6.6.D in [Gro]<sub>FRM</sub> where such a result applies to a refined systolic problem in the spirit of 4.47).

**5.27. Corollary:** *The class  $\mathcal{G}_c$  contains only a finite number of groups isomorphic to the fundamental group of a Riemannian  $n$ -manifold having diameter  $\leq d$  and satisfying  $\text{Ricci}(g) \geq -(n-1)rg$ , for fixed  $n, r, d$ .*

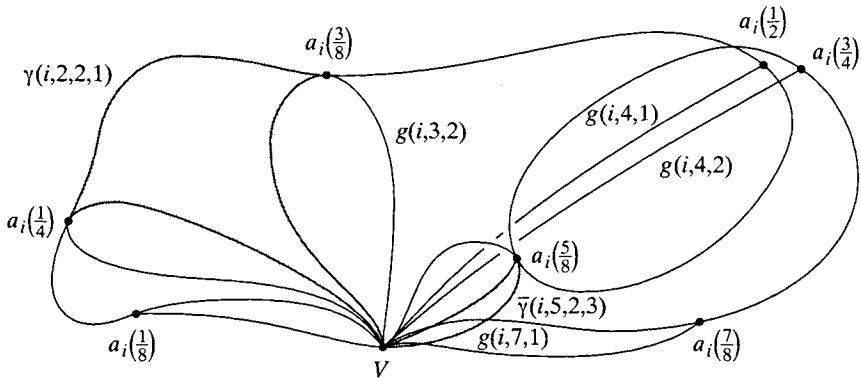
The corollary follows from the preceding theorem and the improved version of Proposition 3.22.

**5.28. Proposition:** *Let  $V$  be a Riemannian manifold of diameter  $d$ . Then for each  $\tilde{v} \in \hat{V}$ , the group  $\pi_1(V)$  admits a finite set of generators  $\gamma_i$  for which  $\|\gamma_i\|_{geo} \leq 2d$  and such that all relations among the  $\gamma_i$  are of the form  $\gamma_i \gamma_j \gamma_k^{-1} = 1$ .*

**Proof.** As in the proof of Proposition 3.22, we choose a finite set of generators  $\alpha_i$  of  $\pi_1(V)$ , and we represent each class  $\alpha_i$  by a loop  $a_i$  based at  $v$ . There exists an  $\varepsilon > 0$  such that the interval  $(2, 2 + \varepsilon)$  does not contain the geometric norm (relative to the point  $\tilde{v} \in \hat{V}$ ) of any element of  $\pi_1(V)$ , and there is an integer  $N$  such that  $\text{length}(a_i)/N < \varepsilon$  for each  $i$ . For  $0 < k < N$ , we connect each point  $a_i(k/N)$  to  $v$  by all possible minimizing geodesics, which we denote by  $g(i, k, j)$ ,  $j \in J$ , where the set of indices may be very large. Let  $\tilde{\gamma}(i, k, j, j')$  be the homotopy class of the loop  $g(i, j, k)g(i, k, j')^{-1}$  and  $\gamma(i, k, j, j')$  is the homotopy class of the loop

$$g(i, k, j)a_i|_{[k/N, k+1/N]}g(i, j+1, j')^{-1}.$$

By construction,  $\|\gamma\|_{geo} \leq 2d + \varepsilon$ , thus  $\leq 2d$  since  $\varepsilon$  is arbitrary. For each  $i$ , we can write  $\alpha_i = \prod_{k=0}^{n-1} \gamma(i, k, j_k, j_{k+1})$  for every sequence  $j_k$  such that the family  $\tilde{\gamma}, \gamma$  generates  $\pi_1(V)$ .



The relations that can exist between the  $\tilde{\gamma}, \gamma$  are, on the one hand, all those which result from the numerous ways of writing the  $\alpha_i$ , i.e., different choices of the sequence  $k \mapsto j_k$ . This reduces easily to the case in which the two sequences  $j_k$  and  $j'_k$  only differ in the  $h$ -th term. Thus, the relation

$$\prod_{k=0}^{n-1} \gamma(i, k, j_k, j_{k+1}) = \prod_{k=0}^{n-1} \gamma(i, k, j'_k, j'_{k+1})$$

amounts to

$$\gamma(i, h-1, j_{h-1}, j_h) \gamma(i, h, j_h, j_{h+1}) = \gamma'(i, h-1, j_{h-1}, j'_h) \gamma'(i, h, j'_h, j_{h+1}),$$

which reduces to the two identities

$$\gamma(i, h, j'_h, j_{h+1}) = \tilde{\gamma}(i, h, j'_h, j_h) \gamma(i, h, j_h, j_{h+1}),$$

$$\gamma(i, h-1, j_{h-1}, j_h) \tilde{\gamma}(i, h, j_h, j'_h) = \gamma(i, h-1, j_{h-1}, j'_h).$$

Other relations arise from the relations among the  $\alpha_i$ .

Let  $\prod_{\ell=1}^p \alpha_{i_\ell}^{e_\ell} = 1$  be one such relation. The loop

$$a_{i_1} \overset{e_1 \text{ times}}{\cdots} a_{i_1} a_{i_2} \overset{e_2 \text{ times}}{\cdots} a_{i_2} \cdots a_{i_p}$$

is divided into segments of length less than  $\varepsilon$ , and the two expressions

$$\prod_{\ell=1}^p \prod_{k=0}^{N-1} \gamma(i_\ell, k, j_k^\ell, j_{k+1}^\ell)$$

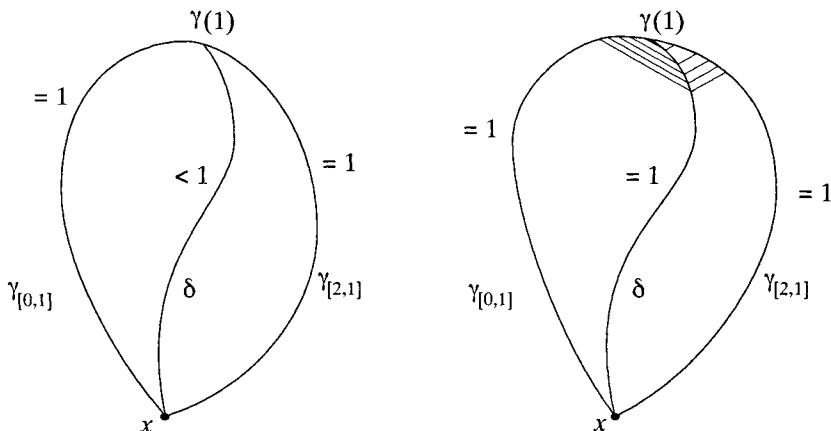
and 1 for the class  $\prod_{\ell=1}^p \alpha_{i_\ell}^{e_\ell}$  are amenable to above-mentioned treatment. We have therefore shown that the group  $\pi_1(V)$  admits a presentation with generators of norm less than  $2d$  and relations of the form  $\gamma_i \gamma_j \gamma_k^{-1} = 1$ .

**5.29. Proof of Corollary 5.27.** Suppose that  $\Gamma \in \mathcal{G}_c$  is isomorphic to the fundamental group of a Riemannian manifold  $(V, g)$  having diameter  $\leq d$  and  $\text{Ricci}(g) \leq -(n-1)rg$ . Then there exists a point  $\tilde{v} \in \tilde{V}$  such that  $\|\cdot\|_{geo}$  does not assume values less than  $c/\sqrt{r}$  on  $\Gamma \setminus \{1\}$ . If  $\gamma_1, \dots, \gamma_p$  is the set of generators of  $\Gamma$  provided by the proposition, then the balls  $B^V(\gamma_i \tilde{a}, c/2\sqrt{r})$  are disjoint in  $B^V(\tilde{v}, 2d + c/2\sqrt{r})$ ; thus their number is bounded by a function  $\psi(n, r, d)$ . The relations among the  $\gamma_i$  are of the form  $\gamma_i \gamma_j \gamma_k^{-1} = 1$ , where the triplet  $(i, j, k)$  denotes a subset of  $R_\Gamma$  of  $\{1, \dots, p\}^3$ . Since the group  $\Gamma$  is determined up to isomorphism by the number  $p$  and the subset  $R_\Gamma$ , the number of possible groups is thus  $\psi(n, r, d)2^{\psi(n, r, d)^2}$ .

**Remark:** It is tempting to ask whether, in the conclusion of Proposition 5.28, one can replace " $\leq 2$ " by " $< 2$ ". The answer is that it can always be done, with the sole exception of the real projective space equipped with its canonical metric. More precisely,

**5.30. Proposition:** *Given an arbitrary point  $x$  in a Riemannian manifold  $(V, g)$  of diameter 1, we can always choose generators  $\gamma_i$  in Proposition 5.28 represented by loops of length  $< 2$ , except when  $V$  is diffeomorphic to  $\mathbb{RP}^n$  and all geodesics based at  $x$  are simple, periodic, and have smallest period equal to 2. If, moreover,  $(V, g) \neq (\mathbb{RP}^n, \text{can})$ , then there is always at least one  $x \in V$  and generators  $\gamma_i$  of  $\pi_1(V)$  that are representable by loops of length  $< 2$ .*

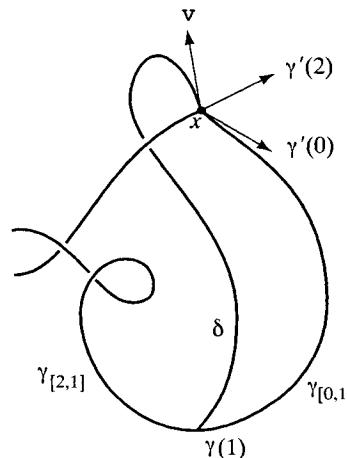
**Proof.** The second assertion follows from the first, combined with Corollary D.2 of [Besse], p. 236.



Fix  $x \in V$  and a nontrivial loop  $\gamma$  based at  $x$  of length 2 and having minimal length in its homotopy class. We may assume that  $\gamma(1)$  lies at

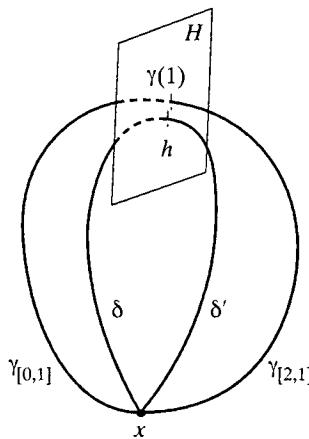
distance 1 from  $x$ . Otherwise, there exists a segment  $\delta$  joining  $x$  to  $\gamma(1)$  with length strictly less than 1, and so  $\gamma$  can be represented by the product of  $\gamma|_{[0,1]} \cup \delta$  and  $\gamma|_{[1,2]} \cup \delta$ , both of which have length less than 2. Similarly, there is no segment  $\delta$  from  $x$  to  $\gamma(1)$  other than  $\gamma|_{[0,1]}$  and  $\gamma|_{[2,1]}$ , since then  $\gamma$  could be represented by the product of  $\gamma|_{[0,1]} \cup \delta$  and  $\gamma|_{[1,2]} \cup \delta$ . These latter loops have length exactly equal to 2, but since they approach  $\gamma(1)$  at an angle other than  $\pi$ , they can be shortened by homotopy.

From this proof and from the equality  $d(x, \gamma(1)) = 1 = \text{diam}(V)$ , we conclude that the geodesic  $\gamma$  is periodic, i.e., the angle at  $x$  between  $\gamma(0)$  and  $\gamma(2)$  is zero. Indeed, if this were not the case, then by an application of Lemma 6.2 of [Che–Ebin] to the points  $p = \gamma(1), q = x$  and to the vector  $v = \gamma(2) - \gamma(0) \in T_v V$ , we would obtain a segment  $\gamma'$  from  $x$  to  $\gamma(1)$  distinct from  $\gamma|_{[0,1]}$  and  $\gamma|_{[2,1]}$ .



We will now show that all geodesics based at  $x$  are of the same nature as  $\gamma$ . For this purpose, we first note that  $\gamma(1)$  is not conjugate to  $x$  on  $\gamma|_{[0,1]}$ , nor on  $\gamma|_{[2,1]}$ , since there would be a curve near  $\gamma$  having strictly smaller length.

Now choose a hypersurface  $H$  passing through  $\gamma(1)$  and transverse to  $\gamma$ . Then  $H$  will intersect each geodesic based at an  $x$  that is sufficiently close to  $\gamma|_{[0,1]}$  or  $\gamma|_{[2,1]}$ . Thus, for each point  $h \in H$  sufficiently close to  $\gamma(1)$ , there is a segment  $\delta$  near  $\gamma|_{[0,1]}$  passing from  $x$  to  $h$ , and a segment  $\delta'$  near  $\gamma|_{[0,1]}$  passing from  $x$  to  $h$ . The union  $\delta \cup \delta'$  is a loop based at  $x$ , homotopic to  $\gamma$ , and of length  $\leq 2$ , since  $\text{diam}(V) \leq 1$ . By the hypothesis on  $\gamma$ , it follows that  $\delta \cup \delta'$  is a geodesic loop based at  $x$ . Thus, all geodesics sufficiently close to  $\gamma$  possess the same initial properties as  $\gamma$  and are therefore simple, closed geodesics having (smallest) period 2. These properties are stable under



closure, and the assertion of the theorem follows, since the unit tangent sphere at  $x$  is connected.

That  $V$  is necessarily diffeomorphic to  $\mathbb{R}P^n$  follows from the last assertion of Theorem 5.3 of [Besse], p. 186–187.

## E<sub>+</sub> Applications of the packing inequalities

**5.31.** The essential property of the manifolds  $(V, g)$  with Ricci curvature bounded from below used in the topological arguments above boils down to the following *packing inequalities*. Say that a metric space  $V$  has *packing type P* for a given  $\mathbb{Z}_+$ -valued function  $P = P(R, r)$  if every ball of radius  $R$  in  $V$  contains at most  $P$  balls of radius  $r$ . (Compare with the *doubling property* in Appendix B<sub>+</sub>.)

Now, the Bishop inequality provides a specific bound on  $P$  in terms of  $\inf \text{Ricci}(g)$ . In particular, *if  $\text{Ricci}(g) \leq -(n-1)g$ , then the packing type P of  $V$  satisfies*

$$P(R, r) \leq C(R/r)^m \quad (*)$$

for  $R \leq 1$  and  $0 \leq r \leq R$ , as well as

$$P(R, r) \leq e^{\alpha R} \quad (**)$$

for  $R \geq 1$  and  $r \geq 1/2$ , and where  $m$  happens to equal  $n = \dim(V)$ , where  $C$  and  $\alpha = \alpha_n$  are universal constants. (In fact,  $P(R, r) \leq C_n(R/r)^n e^{\alpha_n R}$  for all positive  $R$  and  $r$  as we know very well by now.)

**Exercises:** (a) Check that the proofs of 5.3, 5.17, 5.18, 5.21, and 5.24 depend entirely on (the properties of) the packing types of the manifolds in question and of their covering spaces.

(b) Show that the packing bound (type) is implied by a bound on the ratio  $\mu(B(R+r))/\mu(B(r))$ , where  $\mu$  is an arbitrary measure and the  $B'$ s are *concentric* balls. Then prove that a bound on the packing type  $P$  of  $V$  yields a similar bound on the (optimal) *covering numbers* of  $R$ -balls by smaller  $r$ -balls.

(c) **Questions:** Observe that the packing and covering functions of (balls in) metric spaces satisfy certain nontrivial relations. For example, if one can cover  $B(R_3)$  by  $N_3$   $R_2$ -balls and each  $B(R_2)$  by  $N_2$   $R_1$ -balls, then  $B(R_3)$  is covered by  $N_2 N_3$   $R_1$ -balls. For certain pairs  $(R, r)$ , this imposes some relations among the values of the function  $\text{Cov}(V; R, r)$  whose value equals the infimum of the number of  $r$ -balls needed to cover each  $R$ -ball in  $V$ . Similarly, one defines the packing function  $\text{Pa}(V; R, r)$  and asks when a given function  $C(R, r)$  (and  $P(R, r)$ ) can be realized as  $\text{Cov}$  (respectively,  $\text{Pa}$ ) for some metric space  $V$ .

Next, if we have a measure  $\mu$  on  $V$ , we can define

$$\sup \mu = \sup_{v \in V} \mu(B(v, R)) \quad \inf \mu = \inf_{v \in V} \mu(B(v, R)),$$

and

$$\sup \mu(V; R/r) = \sup_{v \in V} \frac{\mu(B(v, R))}{\mu(B(v, r))}.$$

Again, one wishes to know the possible restrictions on these functions. For example, what happens if  $\sup \mu(V; R) = \inf \mu(V; R) = \alpha(R)$  for a given function  $\alpha(R)$ ? (A special case of this problem is treated in [Gro]GPG under the heading of “regular growth.”)

## F<sub>+</sub> On the nilpotency of $\pi_1$

Let  $X$  be a path metric space of packing type satisfying (\*) with some  $m$  (which is allowed here to be different from  $\dim(X)$ ) and  $C > 0$ . Consider some isometries  $\gamma_1, \dots, \gamma_q$  on  $X$ , suppose they generate a *discrete* subgroup  $\Gamma$  in the full isometry group of  $X$ , and set

$$\delta_+ = \max_{1 \leq i \leq q} \text{dist}(x_0, \gamma_i(x_0))$$

for a given point  $x_0 \in X$ .

**Question:** Does there exist a positive  $\varepsilon = \varepsilon(m, C) > 0$  such that the inequality  $\delta_+ < \varepsilon$  would imply that  $\Gamma$  is virtually nilpotent? If not, is  $\Gamma$  at least amenable? And what extra assumptions (if any) does one need to ensure the nilpotency (or amenability) of  $\Gamma$ ?

The positive answer can be achieved with the aid of a *lower* bound on the *minimal* displacement

$$\delta = \inf_{\delta \in \Gamma \setminus \text{id}} \text{dist}(x_0, \gamma(x_0))$$

as follows.

*Let  $\lambda = \delta_+/\delta$ . Then there exists a constant  $\varepsilon = \varepsilon(m, C, \lambda) > 0$  such that the inequality  $\delta_+ \leq \varepsilon$  makes  $\Gamma$  virtually nilpotent.*

This is an easy corollary of the polynomial growth theorem (see §3.4 in [Gro]<sub>VBC</sub>, the last section in [Gro]<sub>GPG</sub>, and 6.6.B in [Gro]<sub>FRM</sub>, where one should note that the definition of  $\delta$  given in [Gro]<sub>FRM</sub> is incorrect).

A more difficult result is due to Cheeger and Colding (see [Che–Col]), who gave a positive answer to our question for Riemannian manifolds with  $\text{Ricci} \leq -(n - 1)$  and with no undesirable  $\delta$ , just for  $\delta_+ \leq \varepsilon$  with  $\varepsilon = \varepsilon(\dim(X)) > 0$ . (They assume that the action of  $\Gamma$  on  $X$  is free and cocompact, but this probably can be easily mended.)

The nilpotency of the group  $\Gamma$  allows a lower bound on the volume of  $V/\Pi$  for some (nonnilpotent) groups  $\Pi$ . For example, *if every virtually nilpotent subgroup  $\Gamma \subset \Pi$  is contained in a unique maximal, virtually nilpotent subgroup  $\Gamma' \subset \Gamma$ , then*

$$\text{vol}(X/\Pi) \geq \varepsilon' = \varepsilon'(m, C, \dim(X)) > 0,$$

*provided that  $\Pi$  is not virtually nilpotent, the action is free, and the classifying map  $X/\Pi \rightarrow K(\Pi; 1)$  is nonhomologous to zero.* (See 6.6.C' in [Gro]<sub>FRM</sub>, where it is stated for  $\text{Ricci} \geq -(n - 1)$ .)

**Exercise:** Generalize the last claim in 6.6.D' of [Gro]<sub>FRM</sub> by replacing the lower Ricci bound by a packing bound.

**5.32. Coverings and mappings to nerves.** Pack a (locally) compact metric space  $V$  by a maximal system of  $R$ -balls  $B_i(R)$  and then take the concentric  $3R$ -balls. These cover  $V$  with good overlaps, which trivially implies the existence of a partition of unity  $\varphi_i$  on  $V$ , all of whose functions  $\varphi_i$  (with supports in the  $B_i(3R)$ ) are  $\lambda$ -Lipschitz with

$$\lambda \leq 3 \text{ multi } /R,$$

where “multi” denotes the multiplicity of the cover. In particular, if the packing type  $P(6R, R)$  is under control, i.e., it is bounded by a given constant  $N_0$ , then so is our multi. Thus, we get a  $\Lambda$  Lipschitz map  $\Phi$  from  $V$  to the nerve  $Q$  of our cover, where  $\Lambda = \sqrt{N_0}\lambda$ , and where the metric we

use in (the simplicial polyhedron)  $Q$  is piecewise Euclidean, built of the  $k$ -simplices

$$\{x_i > 0 : \sum_{i=0}^k x_i = 1\} \subset \mathbb{R}^{k+1} \subset \mathbb{R}^{N_0+1}$$

(compare pp. 85, 86 in [Gro]VBC).

We want to use the maps  $\Phi: V \rightarrow Q$  to bound the topology of  $V$ . To do this, we need control over the contractibility function in  $V$  (see Ch. 3.E<sub>+</sub>) in order to approximately reverse the map  $\Phi$ , say by a  $\Psi: Q \rightarrow V$  such that  $\Psi \circ \Phi: V \rightarrow V$  is homotopic to the identity. If this is the case, and if  $V$  is compact, then we can bound, for instance, the Betti numbers of  $V$  by the number of simplices in  $Q$ . In fact, we can do better, since we need to take into account not all of  $Q$ , but only the image  $\Phi(X) \subset Q$ . Since  $\Phi$  is  $\Lambda$ -Lipschitz, this image is at most  $\Lambda$  times greater than  $X$ . For example, if  $X$  is a Riemannian manifold, then the map  $\Phi$  can be deformed to some  $\Phi'$  which lands in the  $n$ -skeleton  $Q_n \subset Q$  and which is  $\Lambda'$ -Lipschitz with  $\Lambda' < N_0^{N_0} \Lambda$  by a (very) rough estimate. Then the volume of the image does not exceed  $(\Lambda')^n \text{vol}(X)$ , and so we can push  $\Phi'(X) \subset Q_n$  further to a subpolyhedron  $Q'_n \subset Q_n$  consisting of at most  $N$  simplices with  $N \leq n^n (\Lambda')^n \text{vol}(X)$ , thus bounding the Betti numbers of  $X$  by this  $N$ .

There are several possibilities for improvement:

I. Let all of  $V$  or some part  $V_0$  of  $V$  be “thin” (or collapsed), which can be expressed by requiring smallness of some metric invariants of  $V$  or of  $V_0$ . For example,

- (i)  $\text{FilRad } V_0 \leq \varepsilon$ ,
- (ii)  $\text{wid}_m V_0 \leq \varepsilon$ , where  $\text{wid}_m$  denotes the Uryson width of  $V_0$  for some  $m \leq n$ .
- (iii)  $\text{vol } B(R) \leq \varepsilon (R/\Lambda)^n$  for all  $R$ -balls in  $V$ .
- (iv) each  $B(R)$  can be covered by at most  $\varepsilon (R/r\Lambda)^n$  balls of radius  $r$  for a given  $r$  which is significantly smaller than  $R$ .

Then we can push our map  $\Phi': V \rightarrow Q'_n$  to a smaller subpolyhedron containing few  $n$ -simplices (or  $m$ -simplices in the case of (ii)), thus getting a better bound on the topology (e.g., Betti numbers) of  $V$ .

II. It may happen that the balls  $B_i(R)$  are noncontractible (in larger concentric balls) within  $V$ , but there is a map  $f: V \rightarrow K$  into some space  $K$  where these  $B_i(R)$  become contractible. This would allow the homotopy factoring of  $f$  to be

$$f = f' \circ \Phi$$

for some map  $f': Q \rightarrow K$ . As a consequence, we could bound the topological invariants of  $f$ , such as the ranks of the homomorphisms  $f_* : H_*(V) \rightarrow H_*(K)$ .

III. It may happen that the (controlled) contractibility of balls in  $V$  (or in  $K$  receiving  $V$ ) can be gained by passing to some covering of  $V$ . For example, if we start with a compact aspherical space  $V$ , then we do have a controlled contractibility of balls in the universal covering  $X = \tilde{V}$  as well as in the finite coverings  $\tilde{V}_i$  converging to  $\tilde{V}$ . (The existence of such  $\tilde{V}_i$  is equivalent to the *residual finiteness* of  $\pi_1(V)$ , i.e., the existence of subgroups  $\Phi_i \subset \pi_1(V)$  of finite index with  $\bigcap_i \Phi_i = \{\text{id}\}$ ). As we pass to such coverings, we need to *assume* packing inequalities in these (which follow, for example, from a lower bound on  $\text{Ricci}(V)$ ) and instead of the original invariants of  $V$ , we shall come up with a bound on those of  $\tilde{V}$  or of  $\tilde{V}_i$ .

#### IV. Combine I-III.

**Example:** Suppose that  $V$  is an aspherical  $n$ -dimensional manifold with a residually finite fundamental group, where the packing type  $P$  of the universal covering  $X = \tilde{V}$  is under control. Then the above allows a bound on the Betti numbers of  $\tilde{V}_i$  in terms of  $\text{vol } \tilde{V}_i$ . In particular, *one can thus bound the Euler characteristic and the signature of  $\tilde{V}_i$* , and since these invariants are multiplicative under coverings, *one recaptures a bound on  $\chi(V)$  and  $\sigma(V)$  by  $\text{vol}(V)$* . The details can be found in [Gro]VBH, where this is proved in the framework of II.

Our next move is to drop the residual finiteness condition. This will require a more sophisticated formalism which we do not expect a beginner to be ready to swallow (at least not in one gulp).

**5.33. Bounds on  $L_2$ -Betti numbers.** Let us briefly recall the definitions in the special case of a polyhedron  $X$  with a discrete automorphism group  $\Gamma$  acting on  $X$  (where an important example is the Galois action on  $X$  covering some compact  $V$ ). First we define the  *$\ell_2$ -cohomology* of  $X$  (which needs no action) by just restricting to  $\ell_2$ -cochains on  $X$ , i.e., those functions on the set of oriented simplices (or cells) in  $X$  which are square-summable. If  $X$  is uniformly locally finite, i.e., each  $k$ -cell has at most  $N_k$  neighbors for some  $N_k = N_k(X)$ , then the coboundary operator on  $\ell_2$  cochains  $d_k : \ell_2 C^k \rightarrow \ell_2 C^{k+1}$  is  $\ell_2$ -bounded, and then one defines *non-reduced  $\ell_2$ -cohomology* as

$$\ell_2 H^k(X) = \ker d_k / d_{k-1}(\ell_2 C^{k-1}).$$

Of course, it gives you just ordinary cohomology for *finite* polyhedra  $X$ , but if  $X$  is *infinite*, then this reflects the rate of decay of cochains in question.

Also notice that the image  $d_{k-1}(\ell_2 C^k) \subset \ell_2 C^k$  is not necessarily closed, which means that the quotient space ( $\ell_2$ -cohomology) is not a separable space. This is not at all a pathology; yet, sometimes one feels better without it and defines the *reduced  $\ell_2$ -cohomology* as

$$\overline{\ell_2 H}^k(X) = \ker d_k / (\ell_2\text{-closure of } d_{k-1}(\ell_2 C^{k-1})),$$

which is an honest Hilbert space.

At first sight, there is nothing especially interesting about these definitions. True, we get a bi-Lipschitz invariant of  $X$  (this is rather obvious as well as a stronger homotopy invariance in the Lipschitz category), but it carries little information, since all separable infinite-dimensional Hilbert spaces are mutually isometric (and for this reason the non reduced cohomology appears more promising as well as the  $\ell_p$ - generalizations; see [Gro]AI and the references therein).

But a miracle happens when there is a group  $\Gamma$  acting on  $X$ . This does not change the spaces  $\overline{\ell_2 H}^k$  but adds *unitary  $\Gamma$ -actions* to them. Now, an infinite-dimensional Hilbert space  $H$  with a unitary  $\Gamma$ -action can be assigned a certain number, called the *Von-Neumann  $\Gamma$  dimension*, which can be finite since it measures the size of  $H/\Gamma$  in a certain sense. In particular, one can define the  $\ell_2$ -Betti number

$$h^k(X : \Gamma) = \dim_{\Gamma} \overline{\Gamma H}^k(X),$$

which is finite for cocompact actions (i.e., if  $X/\Gamma$  is compact). Here is a direct

**Definition of  $h^k(X : \Gamma)$ :** Let  $d = \bigoplus_k d_k : \ell_2 C^* \rightarrow \ell_2 C^*$ , take the adjoint operator  $d^*$ , and let  $\Delta = dd^* + d^*d$ . Denote by  $\ell_2 \mathcal{H}^k \subset \ell_2 C^k$  the space of *harmonic  $\ell_2$ -cochains* of degree  $k$ , i.e., those in  $\ker \Delta$ , and let  $P^k$  denote the normal projections of  $\ell_2 C^k$  to  $\mathcal{H}^k$ . The projection operator, being  $\ell_2$ -bounded, is given by a “kernel” which is a function  $\Pi(b, b')$  on the pairs of oriented  $k$ -simplices (cells) in  $X$ , such that

$$(P^k(c(b)))(b') = \sum_b \Pi^k(b, b')c(b),$$

where  $\Pi^k$  is skew-symmetric for the change of orientation in the simplices (cells)  $b$  and  $b'$ . Finally, we bring in  $\Gamma$  by noting that the diagonal function  $\text{tr}_k(b) = \Pi^k(b, b')$  is  $\Gamma$ -invariant, and so we can set

$$\text{Tr}_{\Gamma} P^k = \sum_{\underline{b}} (\text{card } \Gamma_{\underline{b}})^{-1} \text{tr}_k(b),$$

where the summation is taken over all  $\Gamma$ -orbits  $\underline{b}$  of cells  $b$  in  $X$ , and where  $\Gamma_{\underline{b}} \subset \Gamma$  denotes the stabilizer (subgroup) of  $b$ . (Notice that  $\text{card } \Gamma_{\underline{b}} = 1$  for free actions.)

These  $\ell_2$ -Betti numbers are clearly finite for cocompact actions, and besides they satisfy the following (easy to prove) properties, which bring them close to the ordinary Betti numbers of  $X/\Gamma$  and especially close to  $i^{-1} \text{rank } H^i(X/\Gamma_i)$  for subgroups  $\Gamma_i \subset \Gamma$  of large index  $i$  (preferably going to infinity, such that  $\bigcap_i \Gamma_i = \{\text{id}\}$ ).

- (a)  $h^k(X : \Gamma) = 0 \Leftrightarrow \overline{\ell_2 H}^k(X) = 0$ .
- (b) If  $X$  is contractible and  $X/\Gamma$  is compact, then the  $h^k(X : \Gamma)$  do not depend on  $X$ , and moreover, the vanishing (or nonvanishing) of  $h^k(\Gamma) \stackrel{\text{def}}{=} h^k(X : \Gamma)$  is a quasi-isometry invariant of  $\Gamma$ .
- (c)  $h^k(\Gamma_1 \times \Gamma_2) = \sum_{i=0}^k h^i(\Gamma_1)h^{k-i}(\Gamma_2)$ .
- (d) The  $\ell_2$ -Euler characteristic  $\chi(X : \Gamma) = \sum_i (-1)^i h^i(X : \Gamma)$  equals  $\chi(X/\Gamma)$  if the action of  $\Gamma$  is cocompact and free.
- (e) If  $\Gamma' \subset \Gamma$  is a subgroup of finite index, then

$$h^k(X : \Gamma') = \text{card}(\Gamma/\Gamma')h^k(X : \Gamma).$$

We suggest that the reader try to prove these properties and consult [Gro]AI and [Lück] for further information and references.

Now we want to explain the following

**$\ell_2$ -bound.** Let  $V$  be a closed, aspherical Riemannian  $n$ -manifold where the packing type of the universal cover satisfies  $P(b, 1) \leq N_0$  (e.g., Ricci  $V \geq -\delta_0$ ). Then the  $\ell_2$ -Betti numbers of the universal covering  $X = \tilde{V}$  acted upon by  $\Gamma = \pi_1(V)$  satisfy

$$\sum_{k=0}^n h^k(X : \Gamma) \leq C \text{vol}(V)$$

for some  $C = C(N_0, n)$ . In particular, the Euler characteristic and the signature of  $V$  are bounded by  $C \text{vol}(V)$  (where the signature is bounded by  $h^{n/2}(X : \Gamma)$  according to the  $L_2$ -index theorem by Atiyah).

**Idea of the proof.** We can cover  $X = \tilde{V}$  by balls of radius 3 with multi  $\leq N_0$ , but such a covering cannot, in general, be made  $\Gamma$ -periodic. But according to the philosophy of A. Connes, “periodic” can be relaxed

to “quasi-periodic” without changing the outcome of the  $\ell_2$ -computation of Betti numbers. This is done by taking some probability space  $M$  with a free, measure preserving action of  $\Gamma$  and then constructing a  $\Gamma$ -*invariant* covering of  $X \times M$  for the diagonal action of  $\Gamma$  on  $X \times M$  by subsets of the form  $B \times M'$ , where  $B = B(3) \subset X$  are balls of radii 3 in  $X$ , and  $M' \subset M$  are measurable subsets. The point is that we can now make such a covering with multiplicity  $\leq N_0$  using the extra freedom given by the action on  $M$ . To see how it works, just look at  $X = \mathbb{R}$  acted upon by  $\mathbb{Z}$  in the usual way. Every equivariant covering here by 3-balls has multiplicity at least 6. But, if we twist it with an irrational action (rotation) of  $\mathbb{Z}$  on  $S^1$ , then  $\mathbb{R} \times S^1$  can be equivariantly covered by  $B(3) \times M'$  with multiplicity at most 2, as a trivial argument shows.

Next, the nerve  $\tilde{Q}$  of the covering of  $X \times M$  by  $B \times M'$  can be used, following Connes, to define the  $\ell_2$ -cohomology and to bound the  $\ell_2$ -Betti numbers in terms of the properly counted “number” of simplices in  $\tilde{Q}$ . Namely, we consider the  $\Gamma$ -orbits  $\underline{\Sigma}$  of our simplices  $\Sigma$  in  $\tilde{Q}$ , where each  $\Sigma$  corresponds to some subsets  $B_i \times M'_i$ ,  $i = 0, \dots, k$  meeting at some point. Every such  $\Sigma$  carries a weight, namely  $\mu\left(\bigcap_{i=0}^k M'_i\right)$ , and the “number” of  $k$ -simplices in  $\tilde{Q} : \Gamma$  is understood as the sum of those weights over all  $\Gamma$ -orbits  $\underline{\Sigma}$  in  $X \times M$ . This is an easy extension (made in a much more general framework by Connes) of the  $\ell_2$ -discussion above.

**Exercise:** Carry out the details in the simplest case of a *trivial* group and then for a nontrivial *finite*  $\Gamma$ , where the von Neumann dimension satisfies

$$\dim_{\Gamma} = \text{rank } H / \text{card } \Gamma.$$

What remains is to bound the “number” of all simplices in  $\tilde{Q} : \Gamma$  by  $C \text{ vol } V$ . Our earlier argument provides such a bound on the number of the  $n$ -simplices, and thus on the number of their  $k$ -faces. But the remaining  $k$ -simplices,  $k < n$ , which are not faces of  $n$ -simplices, do not contribute, due to Poincaré duality for  $\ell_2$ -cohomology. The effect of this is similar to what happens to ordinary Betti numbers: if we have maps  $\Phi : V \rightarrow Q$  and  $\Psi : Q \rightarrow V$ , where  $\Phi \circ \Psi : V \rightarrow V$  is homotopic to the identity, then the Betti numbers of  $V$  in all dimensions are bounded by the number of the  $n$ -simplices in the image of  $\Psi$  times  $2^n$ , provided that  $\dim Q \leq n$  (as we can assume in our case). Also notice that the above fails to be true for general nonsimplicial cell complexes.

**Exercises.** (a) Generalize the above in the spirit of II in (5). Namely, consider a (non-aspherical) space  $V$  mapped to  $K(\Gamma, 1)$ , and bound the von Neumann rank of the (bilinear) cup-pairing on  $\ell_2 H_*(\Gamma)$  associated to

each homology class in  $H_*(\Gamma; \mathbb{R})$  coming from  $H_*(V; \mathbb{R})$ . (Notice that the cup product of two  $\ell_2$ -cohomology cochains on  $X$  is  $\ell_1$  on  $X$  and can be evaluated on each chain in  $X/\Gamma$  equivariantly lifted to  $X$ .)

(b) Extend all of the above to non-Riemannian metric spaces  $V$  where the  $n$ -volume is defined as the supremum of the  $n$ -dimensional Hausdorff measures of the 1-Lipschitz images of  $V$  in Euclidean spaces (compare vol in Ch. 4.C).

**Questions.** How should one modify the above estimates in order to make them (at least roughly) sharp? Can one make the  $\ell_2$ -bounds above with the entropy of  $V$  instead of  $P(6, 1)$  of the universal covering? Can one bound the first  $\ell_2$ -Betti number of a group  $\Gamma$  in terms of the entropy of  $\Gamma$ ?

## G<sub>+</sub> Simplicial volume and entropy

**5.34.** Let us assign a *norm* to the real homologies of topological spaces. This means that we make a *functorial* assignment of a norm to the vector space  $H_k(X; \mathbb{R})$  for *every* topological space  $X$ , where  $H_k$  refers to the *singular* homology of  $X$ , and where *functorial* means that our norm *decreases* under induced homomorphisms  $f_* : H_k(X) \rightarrow H_k(Y)$  for all continuous maps  $X \rightarrow Y$ .

**Examples.** (a) Suppose that  $X$  admits a self-mapping  $f : X \rightarrow X$  sending some  $h \in H_k(X)$  to, say  $2h$ . Then, obviously, the norm of  $h$  must be zero. In particular, our (functorial) norm vanishes on the homology of the  $n$ -torus  $H_k(\mathbb{T}^n)$  for  $k > 0$ . Consequently, it vanishes on the fundamental class of the sphere  $S^n$ , since this comes from  $\mathbb{T}^n$  by some map  $\mathbb{T}^n \rightarrow S^n$  (of degree 1). Furthermore, there is no nonzero norm on  $H_1(X)$ , since every homology class comes from  $S^1 = \mathbb{T}^1$ .

(b) Now look at  $H_2(X)$  and observe that every (integral rather than real) 2-dimensional class (cycle) can be represented by a map of a surface  $S$  into  $X$ . If the genus of  $S$  is zero or one, this surface has zero norm and can be discarded. On the other hand, surfaces of genus  $\geq 2$  do admit a nonzero norm by the following trivial

**5.35. Mapping lemma:** *Let  $f : S \rightarrow S'$  be a map of degree  $d$  between connected, oriented surfaces of negative Euler characteristics. Then*

$$|\chi(S)| \geq d|\chi(S')|.$$

Thus,  $|\chi(S)|$  serves as a norm in the category of surfaces, and it extends to all  $X$  as the maximal norm compatible with the assignments above for

surfaces. Namely, for a given  $h \in H_2(X; \mathbb{Z})$ , we consider all surfaces  $S$  and maps  $f: S \rightarrow X$  with  $f_*[S] = mh$  and define

$$\text{norm}(h) = \inf_{m, S, f} m^{-1} \text{norm}[S],$$

where the infimum runs over all  $m = 1, 2, \dots$ , all connected surfaces of genus  $\geq 2$ , and all  $f$  above. Clearly, this makes a norm on  $H_2(X; \mathbb{Z}) \otimes \mathbb{R}$  (which is somewhat different from  $H_2(X; \mathbb{R})$  if  $H_2$  is not finitely generated) with our starting  $\text{norm}[S] = |\chi(S)|$ .

**Exercise.** Describe *all* possible functorial norms on  $H_2$  in the category of surfaces.

**Remarks:** (a) The interpretation of  $|\chi(S)|$  as a norm originates from a work by Thurston, who used this idea to define a norm on  $H_2(X^3)$  using surfaces *embedded* into 3-manifolds.

(b) We shall meet below a wild variety of norms, all directly or indirectly associated to the fundamental group  $\pi_1(X)$  (compare (4)(A) below). It is probable that every natural norm vanishes on  $H_*(X)$  for all simply connected  $X$ .

**5.36. Norm on  $[S_1 \times S_2 \times \dots \times S_l]$ .** Now it is tempting to define the norm on (the fundamental classes) of products of surfaces with  $\chi < 0$  by

$$\|[S_1 \times S_2 \times \dots \times S_l]\|_\chi = |\chi(S_1 \times S_2 \times \dots \times S_l)|,$$

and then to extend it to  $H_k(X)$ ,  $k = 2l$ , for all  $X$  by the above reasoning. Indeed, this is possible due to

**Another mapping lemma:** *Let*

$$f: S_1 \times S_2 \times \dots \times S_l \rightarrow S'_1 \times S'_2 \times \dots \times S'_l$$

*be a map of degree  $d$ . Then*

$$|\chi(S_1 \times S_2 \times \dots \times S_l)| \geq d|\chi(S'_1 \times S'_2 \times \dots \times S'_l)|.$$

There are at least three different proofs of this lemma. One is based on the Lusztig-Meyer signature theorem (see [Gro]PCMD); the second proof (which was probably the first chronologically) appeals to the proportionality principle for the simplicial volume (see below), and the third one (which is a variation of the first) was more recently suggested by Besson, Courtois, and Gallot. (See [Pan]VCE for an exposition of their work. Actually, I am not certain that their argument was carried over for products of surfaces.)

So, one can feel comfortable with  $S_1 \times S_2 \times \cdots \times S_l$ , but, as for general  $X$ , it is unclear which  $2l$ -dimensional classes in  $H_{2l}(X)$  come from (mapped) products of surfaces (if there is not enough maps  $S_1 \times S_2 \times \cdots \times S_l \rightarrow X$ , we end up with an *infinite* norm on  $H_{2l}(X)$ ). Probably most (interesting)  $2l$ -classes do *not* arise in this way (e.g., one suspects that the fundamental classes of irreducible, locally symmetric spaces admit no such maps), but *not a single* example has been worked out. In any case, one can be relieved with the following definition, which gives a finite (possibly zero) norm to every class.

**5.37. Simplicial norm.** Recall that every real singular  $k$  chain in  $X$  is a formal real combination of singular simplices

$$c = \sum_{i=1}^p r_i \sigma_i,$$

for  $\sigma_i : \Sigma^k \rightarrow X$ . Then  $\sum_{i=1}^p |r_i|$  gives us a norm on the chains. This norm restricts to cycles and then passes to the quotient norm on homology classes. In other words, the simplicial norm  $\|h\|_\Delta$  for an  $h \in H_k(X)$  is the minimal “number” of simplices needed to represent  $h$  by a singular cycle. For example, if  $h$  is the fundamental class of an oriented manifold  $V$ , then  $\|h\|_\Delta = \| [V] \|_\Delta$  is obviously majorized by the number of the top-dimensional simplices needed to triangulate  $V$ . In fact, one can think of  $\| [V] \|_\Delta$  as the infimum of the number of simplices over all ideal (homotopy) triangulations of  $V$ , where one allows non-embedded simplices. This is especially transparent if  $V$  is a Riemannian flat (or almost flat) manifold, so that one can speak of standard Euclidean (or almost Euclidean) simplices isometrically *immersed* (not necessarily embedded!) into  $V$  and fitting into a cycle homologous to  $[V]$ . The simplest instance of this is given by a triangulation of a  $d$ -sheeted covering  $\tilde{V}_d \rightarrow V$ , where  $[V]$  is represented by the simplices of some triangulation of  $\tilde{V}_d$  with weights  $1/d$ . In fact, this procedure leads to a sharp evaluation of the simplicial norm for surfaces.

**Exercise:** Show that every oriented surface of genus  $\geq 2$  satisfies

$$\|[S]\|_\Delta = 2|\chi(S)|.$$

This is elementary. What is trickier is a similar *proportionality theorem* for other compact, locally homogeneous spaces  $V$ ,

$$\|[V]\|_\Delta = c \operatorname{vol}(V),$$

where the constant  $c$  depends on the local geometry of  $V$ . This  $c$  is explicitly known for  $V$  of constant negative curvature, and it is nonzero for most

(probably all) locally symmetric spaces with  $\text{Ricci} < 0$  (see [Pan] and the references therein).

**5.38. Upper bound on  $\|\cdot\|_\Delta$ .** Now we have enough examples of nonzero simplicial norms to become interested in *upper bounds*.

**Theorem:** *Let the universal covering  $X = \tilde{V}$  of  $V$  have packing type such that  $P(b, 1) < N_0$ . Then every homology class  $h \in H_k(V; \mathbb{R})$  satisfies*

$$\|h\|_\Delta \leq \text{const}(k, N_0) \|h\|_{\text{mass}}$$

for the mass norm defined in 4.15.

**Idea of the proof.** We proceed as in 5.34. In order to make that argument work, we shall need two essential properties of the simplicial norm.

(A)  **$\pi_1$ -essentiality.** *Let  $f: V \rightarrow K(\Gamma; 1)$  be the classifying map for  $\Gamma = \pi_1(V)$ . Then  $f_*: H_*(V; \mathbb{R}) \rightarrow H_*(K(\Gamma; 1); \mathbb{R})$  is isometric with respect to the simplicial norm. (See [Gro]<sub>VBC</sub>.)*

Now, if the group  $\Gamma = \pi_1(V)$  is residually finite  $\Gamma$ , then we can pass to a finite  $d$ -sheeted covering  $\tilde{V}_d$  of  $V$  and use the nerve of a suitable cover of  $\tilde{V}_d$  by balls as a “triangulation” of the image  $f_*(d[V]) \in H_*(K(\Gamma; 1))$  with the number of simplices controlled by  $\text{vol}(\tilde{V}_d) = d \text{vol } V$  exactly as we did in 5.33. This takes care of  $h = [V]$  and the rest of  $H_*(V)$  is treated similarly.

Next, we must face the general case of non-residually finite  $\Gamma$ , and for this we need an extension of  $\|\cdot\|_\Delta$  to *foliations with transversal measures*. This was suggested by A. Connes (unpublished) and presented in [Gro]<sub>FPP</sub>. Here we explain the idea of Connes in the framework of our discussion in 5.34, and so we assume, to save notation, that  $V$  is aspherical and therefore plays the role of  $K(\Gamma; 1)$  with  $f$  being the identity map. Then instead of triangulating some  $\tilde{V}_d$ , we equivariantly “triangulate”  $X \times M$  (where  $X = \tilde{V}$  and  $M$  is some probability  $\Gamma$ -space). The claim is that this gives the same value to the simplicial norm as the one we obtain with real cochains in  $V = X/\Gamma$ . In fact, there are *a priori* two distinct definitions of the *simplicial volume* of  $(X \times M)/\Gamma$ . The first one uses *integral* measurable chains: here *measurable  $k$ -simplices* are  $\Gamma$ -equivariant measurable maps

$$\sigma: \Delta^k \times \Gamma \times M' \rightarrow X \times M,$$

where each  $\Delta^k \times \gamma \times m'$  goes to a single fiber  $X \times m$ , and where the resulting maps  $M'_\gamma = \gamma \times M' \rightarrow M$  are measure preserving for each  $\gamma \in \Gamma$ . One builds the integral and the real chain complexes out of these  $\sigma$  with

chains  $c = \sum_i r_i \sigma_i$ , where the norm is defined as

$$\|c\|_{\Delta} = \sum_i |r_i| \mu(M'_i).$$

These integral and real chain complexes project to the corresponding singular chain complexes of  $V$ , and so one can speak of the representation of the homology of  $V$  by measurable chains. In particular, one applies this to the fundamental class  $[V]$  and defines the integral and real simplicial  $M$ -volumes by taking the infima of the norms of such representation, denoted

$$\|[V]_{\mathbb{Z}}\|_{\Delta}^M \quad \text{and} \quad \|[V]_{\mathbb{R}}\|_{\Delta}^M.$$

(Notice that we could also define the simplicial norm  $\|[V]_{\mathbb{Z}}\|_{\Delta}$  without any  $M$  by using *integral* singular chains representing  $[V]$ , but this would give us rather unruly objects.) It is clear that

$$\|[V]_{\mathbb{Z}}\|_{\Delta}^M \geq \|[V]_{\mathbb{R}}\|_{\Delta}^M$$

for all probability  $\Gamma$ -spaces  $M$  and by Connes' theorem (see [Gro]FPP), we have

$$\|[V]\|_{\Delta} = \|[V]_{\mathbb{R}}\|_{\Delta}^M \tag{*}$$

for all  $M$ .

**Exercise:** Derive the above-mentioned proportionality of  $\|[V]\|_{\Delta}$  from (\*).

We are now justified in defining the integral foliated simplicial volume as

$$\|[V]_{\mathbb{Z}}\|_{\Delta}^{\mathcal{F}} = \inf_M \|[V]_{\mathbb{Z}}\|_{\Delta}^M$$

over all probability  $\Gamma$ -spaces  $M$ . Clearly, this majorizes the ordinary simplicial volume  $\|[V]\|_{\Delta}$  and, on the other hand, it can be majorized by  $\text{vol } V$  by the argument in 5.34. This concludes our sketch of the proof of the upper bound on  $\|[V]\|_{\Delta}$ .

**Remarks and exercises:** (a) Fill in the details in the argument (consulting the cited papers when necessary).

- (b) Work out the case of  $h \neq [V]$  and also of  $V \neq K(\Gamma; 1)$ .
- (c) Obviously (with (\*)),

$$\|[V]\|_{\Delta} \leq \|[V]_{\mathbb{Z}}\|_{\Delta}^{\mathcal{F}},$$

and so we bounded something better than  $\|[V]\|_{\Delta}$ . But the two invariants may be equal for all we know to date.

(d) One may relax the definitions of  $\|[V]_{\mathbb{Z}}\|_{\Delta}^M$  and  $\|[V]_{\mathbb{R}}\|_{\Delta}^M$  by allowing infinite chains  $\sum_i r_i \sigma_i$  with  $\sum_i |r_i| \mu(M'_i) < \infty$ . This does not change  $\|[V]_{\mathbb{R}}\|_{\Delta}^M$  but may (?) diminish  $\|[V]_{\mathbb{Z}}\|_{\Delta}^M$ .

(e) Show that the sum of the  $\ell_2$ -Betti numbers of  $V = X/\Gamma$  satisfies

$$\sum_{k=0}^n h^k(X; \Gamma) \leq 2^n \|[V]_{\mathbb{Z}}\|_{\Delta}^{\mathcal{F}}$$

for all closed  $n$ -dimensional aspherical manifolds  $V$ . Extend this to non-aspherical  $V$  mapped to  $K(\Gamma; 1)$ 's and thus generalize the  $\ell_2$ -bound in 5.34. (One does not know if similar results hold with  $\mathbb{R}$  in place of  $\mathbb{Z}$ .)

**5.39. Bound for  $\|[V]\|_{\Delta}$  by entropy.** The following discussion sharpens the bound above for the simplicial volume, however it does not apply to  $\|[V]_{\mathbb{Z}}\|_{\Delta}^{\mathcal{F}}$  any more.

**Theorem.**

$$\|[V]\|_{\Delta} \leq c_n(h(V))^n \text{vol}(V) \quad (\star)$$

for some universal constant  $c_n$  (see p. 37 in [Gro]<sub>VBC</sub> for the proof).

Notice that the constant given in [Gro]<sub>VBC</sub> is not sharp. In fact,  $(\star)$  was originally proved by A. Katok (see [Katok]) for surfaces with sharp  $c_2$  (and  $\chi(V)$  instead of  $\|[V]\|_{\Delta}$ ), who employed a conformal change of the metric to constant curvature with a subsequent use of the length-area method (compare [Gro]<sub>FRM</sub>). Recently, several sharp versions of  $(\star)$  were obtained by Besson, Courtois, and Gallot (see [Pan]<sub>VCE</sub>).

We conclude by observing that  $(\star)$  provides a *lower* bound on the volume growth of  $X = \tilde{V}$  in terms of  $\text{vol}(V)$  and a purely topological invariant, the simplicial volume  $\|[V]\|_{\Delta}$  of  $V$ .

## H<sub>+</sub> Generalized simplicial norms and the metrization of homotopy theory

We start with several straightforward modifications of the definition of  $\|\cdot\|_{\Delta}$ .

**5.40. Cubical norm, etc.** It does not take much imagination to pass from the simplicial to *cubical* singular homology theory and to define the cubical norms  $\|\cdot\|_{\square}$  on  $H_k(X)$  accordingly. It is obvious that the two norms are *equivalent*, i.e.,

$$C_k \leq \frac{\|h\|_{\Delta}}{\|h\|_{\square}} \leq C'_k$$

for some  $C_k, C'_k$ , but the *exact* values of these constants are unknown. It is even possible (albeit unlikely) that  $\|h\|_\Delta = A_k \|h\|_\square$  for some universal constant  $A_k$ .

One can go further in this direction and use more complicated cells to build up singular chains. The smallest such norm corresponds to the minimal number of cells in cellular decompositions of a space  $P$ . Using this number  $\text{cell}(h)$ ,  $h \in H_k(X)$ , realizing  $h$  by a map of an oriented pseudomanifold  $P$  with minimal possible number  $\text{cell}(P)$ . This becomes a true norm after stabilization

$$\|h\|_{\text{cell}} = \lim_{i \rightarrow \infty} i^{-1} \text{cell}(ih).$$

One knows that this norm is nonzero on the fundamental classes of products of surfaces (see [Gro]PCMD) and, more generally, is nonzero on the fundamental classes of locally symmetric spaces  $X$  with  $\text{Ricci}(X) < 0$  and  $\chi(X) \neq 0$  (see [Lustig]).

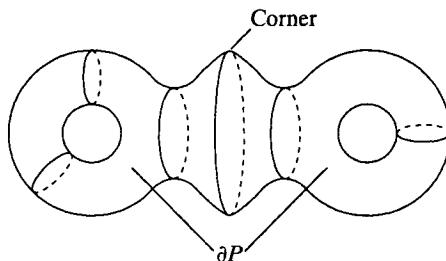
Rather than starting with cells, one can start with topologically more complicated manifolds (and pseudomanifolds  $V$  with boundaries subdivided (stratified) further in a cell-like fashion. For example, the standard simplex and cube are organized in this manner. But we can also admit some manifolds with or without (non-subdivided) boundaries or products of such with obviously subdivided boundaries,  $W = V_1 \times V_2$ , with

$$\partial W = (V_1 \times \partial V_2) \cup (\partial V_1 \times V_2).$$

Now, given such  $V$ , we try to assign to it some (simplicial-like) norm  $\|V\|$  for which we want to satisfy the inequality  $\|V_1\| \geq d\|V_2\|$  in the presence of a continuous map  $V_1 \rightarrow V_2$  of degree  $d$  sending strata to strata. Furthermore, whenever  $V$  is assembled out of  $V_i$  with strata-preserving gluing maps on the pieces of the boundaries (as for pseudomanifolds being made out of the top-dimensional simplices), we want  $\|V\| \leq \sum_i \|V_i\|$  (and if this fails, it should be attributed to some “norm” on the gluing maps). So, we may start with some collection of  $V_i$ ,  $i = 1, \dots, j$ , assign a number (weight)  $\alpha_j$  to each of them, and then define the maximal possible norm on all  $V$ 's satisfying the requirements above. For example, if  $\{V_i\}$  consists of the single simplex  $\Delta^k$  with weight 1, then we recapture our simplicial norm. Or, we could start with  $V_i$  being products of surfaces with weights  $|\chi(V_i)|$  as earlier.

Thus, one is led to a variety of combinatorially defined norms on the homology of spaces as well as on the (fundamental) homology classes of stratified spaces. (Notice that  $\Delta^k$  admits no face-preserving map of degree  $d \geq 2$ , and so its “stratified norm” does not have to vanish.)

A particularly interesting class of examples is furnished by *hyperbolic polyhedra*  $P$  of the form  $\tilde{P}/\Gamma$  for convex polyhedra  $\tilde{P}$  in the hyperbolic space  $H^n$ . A case we want to emphasize is where neither  $P$  nor  $\tilde{P}$  have vertices and perhaps not even 1-strata. For example,  $P$  may be a hyperbolic manifold with *totally geodesic* boundary, or a boundary made up of two hyperbolic  $(n-1)$ -manifolds meeting along *their* totally geodesic boundaries with a corner, and so on.



One can assemble more complicated spaces out of these polyhedra  $P$  by gluing them (isometrically, to be prudent) along the boundary strata. For example, some ramified coverings of hyperbolic manifolds with totally geodesic ramification loci come about this way (see [Gro-Thu]).

**Problems:** Compute the simplicial norms of manifolds assembled out of these polyhedra, e.g., of the above ramified coverings. Study the norms associated to specific collections of such polyhedra. Can two such norms ever be mutually proportional without being *obviously* proportional? Are all of these norms equivalent to the simplicial norm unless for some obvious reason to the contrary?

**5.41. Norms on  $H_k$  defined via the geometry of cycles.** Given a closed  $k$ -dimensional manifold or pseudomanifold  $V$ , one considers a class  $\mathcal{G}$  of metrics on  $V$  and defines  $\min_{\mathcal{G}} \text{vol}(V)$  as the infimum of the volumes of all metrics  $g \in \mathcal{G}$  on  $V$ . In what follows, this class  $\mathcal{G}$  is essentially independent of  $V$ , and so one may speak of  $\text{vol}_{\mathcal{G}}(h)$ ,  $h \in H_k(X)$ , as the infimum of  $\min_{\mathcal{G}} \text{vol}(V)$  for all  $V$  realizing  $h$  (i.e.,  $h = f_*[V]$  for some continuous map  $f: V \rightarrow X$ ). Finally, one stabilizes and sets

$$\|h\|_{\mathcal{G}} = \lim_{i \rightarrow \infty} i^{-1} \text{vol}_{\mathcal{G}}(ih).$$

**Examples:** (a) Let  $\mathcal{G}$  consist of piecewise Euclidean metrics such that each  $V$  is built of regular unit  $k$ -simplices  $\Delta^k$ . Then the volume of such  $V$  equals the number of  $\Delta^k$ 's, and the norm  $\|\cdot\|_{\mathcal{G}}$  is proportional to  $\|\cdot\|_{\Delta}$ .

(b) One can modify the above by insisting that there are at most  $N_\ell$   $k$ -simplices adjacent to each  $\ell$ -face in (the triangulation) of  $V$ . This gives an *a priori* larger norm than  $\|\cdot\|_\Delta$ . Probably all such norms for sufficiently large  $N_\ell$  are mutually equivalent (this seems easy), but it is unclear if these are equivalent to  $\|\cdot\|_\Delta$ . (This is related to the combinatorial filling problem from 5 $\frac{5}{7}$  of [Gro]PCMD solved for  $k - 1 = 2$ , which implies a positive answer to the question above for  $k = 3$ .)

(c) Now we take a more geometric stance and look at the following classes of metrics:

$$\begin{aligned}\mathcal{G}_1 &= \{g : |K(g)| \leq 1, \text{InjRad}(g) \geq 1\}, \\ \mathcal{G}_2 &= \{g : |K(g)| \leq 1\}, \\ \mathcal{G}_3 &= \{g : K(g) \geq -1\}, \\ \mathcal{G}_4 &= \{g : \text{Ricci}(g) \geq -(k-1)g\}, \\ \mathcal{G}_5 &= \{g : \text{Sc}(g) \geq -k(k-1)\},\end{aligned}$$

where  $K$  denotes the sectional curvature and  $\text{Sc}$  is the scalar curvature. Obviously,

$$\mathcal{G}_1 \subset \mathcal{G}_2 \subset \mathcal{G}_3 \subset \mathcal{G}_4 \subset \mathcal{G}_5.$$

It is also clear that the norm  $\|\cdot\|_{\mathcal{G}_1}$  is equivalent to the one in (b) with sufficiently large (locally complex numbers)  $N_\ell$ . Essentially all we know about these norms is that  $\|\cdot\|_{\mathcal{G}_4}$  dominates  $\|\cdot\|_\Delta$ ,

$$\|\cdot\|_\Delta \leq \text{const}_k \|\cdot\|_{\mathcal{G}_4}.$$

The most interesting and mysterious is the norm  $\mathcal{G}_5$ . One would be happy to prove that it is *not* identically zero. (This may follow for  $k = 3$  from the recent work by M. Anderson on the geometrization conjecture.)

One can continue with such questions further revealing our ignorance about the basic topology-geometry interaction. For example, one could look at the class  $\mathcal{G}'_4$  consisting of the metric  $g$  with respect to which  $(V, g)$  has a small covering entropy, say  $h \leq \log 2$  (i.e., the volume growth of the  $R$ -balls in the universal cover is bounded by  $\text{vol } \tilde{B}(R) \leq 2^R$  for  $R \rightarrow \infty$ ). This again is known to dominate  $\|\cdot\|_\Delta$ , but one does not know if this  $\|\cdot\|_{\mathcal{G}'_4}$  is equivalent to  $\|\cdot\|_\Delta$ . Also, one could restrict  $g$  by means of the systole  $\text{syst}_1(V, g)$ . Namely, one may define  $\min_{sy} \text{vol}(V)$  as the supremal number  $\sigma \geq 0$  such that

$$\text{syst}_1(V, g) \leq \sigma^{-1/n} \log(1 + \sigma) \text{vol}(V, g)^{1/n}$$

for all metrics  $g$  on  $V$ , and then set  $\text{vol}_{sy}(h)$  and  $\|h\|_{sy}$  accordingly. Again, this definition is motivated by the bound  $\|\cdot\|_\Delta \leq \text{const}_k \|\cdot\|_{sy}$  (see [Gro]FRM).

Finally, one may introduce integral versions of the classes  $\mathcal{G}_1 - \mathcal{G}_5$  and the corresponding norm on  $H_*(X)$ . Namely, one could minimize the integrals of  $|K(g)|^{k/2}$ ,  $|K_-|^{k/2}$ ,  $\|\text{Ricci}_-\|^{k/2}$  and  $|\text{Sc}_-|^{k/2}$  over  $(V, dg)$ , where  $f_-(v) = \min(0, f(v))$  at all  $v \in V$ , instead of the volumes of  $g$ . Again, we do not know if either of the resulting norms is *not* identically zero. The easiest case is that of the full sectional curvature, and yet we have no examples of a class  $h \in H_k(X)$ ,  $k \geq 3$ , for some  $X$ , such that every Riemannian manifold  $(V, g)$  admitting a continuous map  $V \rightarrow X$  sending  $[V]$  to  $ih_k$  satisfies

$$i^{-1} \int_V |K(g)|^{k/2} dg \geq \varepsilon = \varepsilon(h) > 0$$

for all  $i \in \mathbb{Z}$ . (The situation is slightly more cheerful for *bordism* classes instead of homology, where the lower bounds on  $\int |K|^{k/2}$  come from characteristic numbers. (See [Gro]PCMD for more interesting geometric bordism invariants.)

**5.42. Intrinsic metrics on homotopy types of spaces.** Given a topological space  $X$ , we want to construct in a functorial way a metric space  $\mathcal{X}$  which is homotopy equivalent to  $X$  so that continuous maps  $X \rightarrow Y$  would transform into *distance decreasing* maps  $\mathcal{X} \rightarrow \mathcal{Y}$ . Then we could define the volumes and  $\mathbb{R}$ -masses on the homology  $H_*(\mathcal{X}) = H_*(X)$ , thus getting new norms of the above kind.

There is one standard construction which assigns to every  $X$  a simplicial polyhedron  $\mathcal{X}$  as follows. Take an arbitrary countable subset  $\mathcal{X}_0 \subset X$  for the vertex set of  $\mathcal{X}$ , where we assume that  $X$  is connected and consists of more than a single point. Then use the homotopy classes of paths in  $X$  between distinct  $x_i \in \mathcal{X}_0 \subset X$  for edges. Next, fill all triangles of paths in  $X$  by all possible homotopy types of maps of the 2-simplex  $\Delta^2 \rightarrow X$ , and so on. Thus, one gets our  $\mathcal{X}_0$  with a distinguished homotopy equivalence  $\mathcal{X}_0 \rightarrow X$  (compare pp. 41-48 in [Gro]VBC). This  $\mathcal{X}_0$  is built of infinitely many simplices  $\Delta^k$ ,  $k = 0, 1, \dots$ , and one can give  $\mathcal{X}_0$  a metric by assigning some metrics to the standard simplices  $\Delta^k$ ,  $k = 1, 2, \dots$ , so that this assignment on  $\Gamma^{k1}$  agrees with the restriction of the metric on  $\Delta^k$  to the  $(k-1)$ -faces.

There are innumerable many such metrics; here are a few which immediately come to mind.

- (i) Take the standard Euclidean metric on each  $\Delta^k = \{x_i \geq 0 : \sum_{i=0}^k x_i = 1\} \subset \mathbb{R}^{k+1}$ .

- (ii) Use the spherical metric on the above  $\Delta^k$  radially projected to  $S^k \subset \mathbb{R}^{k+1}$ .
- (iii) Try the metric induced from the  $\ell_1$ -norm on  $\mathbb{R}^{k+1}$ .

One can show in this regard that a suitably normalized  $\mathbb{R}$ -mass in (iii) equals the simplicial norm  $\|\cdot\|_\Delta$  (compare pp. 91–92 in [Gro]VBC). We suggest this as an exercise for the reader. It also seems not hard to show that the norms coming from (ii) and (iii) are mutually equivalent, but (i), I am afraid, always leads to the identically zero norm.

**Question:** Do the norms coming from the function  $X \rightsquigarrow \mathcal{X}_0$  exhaust all possible norms on homology with suitable metrics on  $\Delta^k$ ? Or, can one gain in generality by using more complicated  $\mathcal{X}$ 's? (e.g., built of cubes mapped to  $X$ .)

In practice, a space  $\mathcal{X}$  may appear not exactly as the above  $\mathcal{X}_0$ . For example, the simplicial volume comes along with the natural action of a group  $\Gamma$  on the space  $\Delta^\infty(\Gamma)$  of all probability measures on  $\Gamma$  with the  $\ell_1$  metric. The action of  $\Gamma$  on this  $\Delta^\infty$  is not quite free ( $\Gamma$  may have torsion), but nevertheless the real homology of  $\Gamma$  can be realized by cycles in  $\Delta^\infty/\Gamma$  or, better, by  $\Gamma$ -equivariant cycles in  $\Delta^\infty$ . Thus, a suitable  $\ell_1$ -volume on  $k$ -chains in  $\Delta^\infty$  leads to the simplicial norm on  $H_*(\Gamma)$  (compare 2.4 in [Gro]VBC). One wonders what happens here for other natural metrics on  $\Delta^\infty$ , e.g., the spherical one. Furthermore, one may try different actions of  $\Gamma$  on function spaces, e.g., the regular representation on the unit sphere  $S^\infty \subset \ell_2(\Gamma)$ . Also, if the group  $\Gamma$  is hyperbolic, then one has an action on the space of measures on the ideal boundary  $\partial\Gamma$ , and if this boundary happens to come with a  $C^1$ -structure (as for 1/4-pinched hyperbolic manifolds), then one can use the Hilbert space of 1/2-densities on  $\partial\Gamma$  (as in [B–C–G], where the authors employ this idea for  $\Gamma$  action on the ideal boundaries of symmetric spaces of  $\mathbb{R}$ -rank one).

**Problem:** Study the volume “norm” and the  $\mathbb{R}$ -mass norm on the homology of natural function spaces  $X$ , especially those of the form  $X = \tilde{X}/\Gamma$ . Study the Plateau problem in these  $X$  and identify whenever possible the minimal subvarieties.

We have already encountered this problem in the systolic framework, but our present pool of spaces  $X$  seems different from the one in Ch. 4 where the geometry was tilted to  $L_\infty$  rather than to  $L_1$ , as in the simplicial volume picture.

**5.43. Thurston's idea of straight simplices.** The present conception

of the simplicial volume has grown out of the following startling geometric observation made by Thurston about 20 years ago. Let  $V$  be a complete manifold with constant negative curvature, let  $P$  be a simplicial polyhedron of dimension  $k$ , and let  $f_0: P \rightarrow V$  be a continuous map. Then  $f_0$  can be deformed to a map  $f$  such that *the  $k$  dimensional volume of the image  $f(P)$  (counted with multiplicity if the need arises) is bounded by a constant times the number of  $k$ -simplices in  $P$ , provided that  $k \geq 2$ . For example, if both  $P$  and  $V$  are closed  $k$ -dimensional manifolds, then there is a bound on the degree of  $f$  in terms of the topology of  $P$  (see [Thurs]).*

This was, of course, well-known prior to Thurston in the case of  $k = 2$ , at least for maps of surfaces into  $V^n$ ,  $n \geq 2$ , since one could deform  $f_0$  to some *minimal* (say harmonic) map  $f$  and then use Gauss-Bonnet. But no tool was in sight for  $k \geq 3$ . In fact, it was not even clear why one could not significantly enlarge the volume of a hyperbolic manifold by deforming the metric while keeping the curvature below  $-1$ , although it had an irresistible appeal to one's geometric intuition. Then one day the following breathtaking argument (that only Thurston could come up with) was unloaded on me by Dennis Sullivan:

Straighten the map on every simplex  $\Sigma^i$  from  $P$  mapped to  $V$ . Namely, first deform each edge to the geodesic segment between the images of the vertices, then deform the curved 2-simplices to totally geodesic ones, and so on. Now we have an  $f$  sending each simplex  $\Delta^k$  in  $P$  to a totally geodesic simplex  $\underline{\Delta}^k$  in  $V$  where

$$\text{vol}_k \underline{\Delta}^k \leq \sigma_k < \infty$$

for  $k \geq 2$ , as everybody since Lobachevskii knows.

Actually, Dennis brought up this argument to justify the question he posed:

*Does the degree of a continuous map  $f: V_1 \rightarrow V_2$  between equidimensional hyperbolic (i.e., with  $K = -1$ ) manifolds satisfy*

$$\deg f \leq \frac{\text{vol } V_1}{\text{vol } V_2} ? \quad (*)$$

(It could have been a slightly different question in the same spirit.) And then, he shot me with the “straightening” proof in order to arrest the flow of my objections to the feasibility of obtaining (\*), even in a non-sharp version, by means of the hyperbolic geometry available at the time.

The straightening argument, when applied to singular real chains in  $V$ , instantaneously bounds the  $\mathbb{R}$ -mass by the simplicial norm

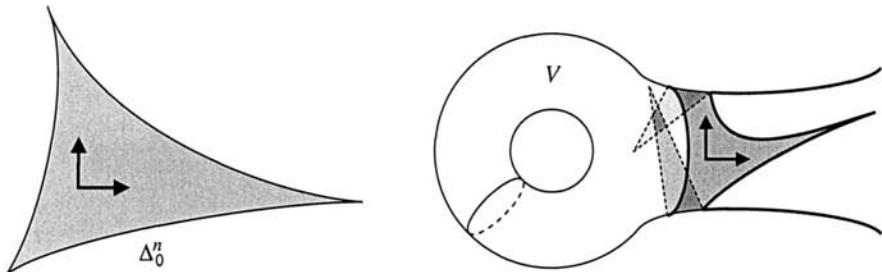
$$\|h\|_{\text{mass}} \leq \sigma_k \|h\|_{\Delta}, \quad (+)$$

where  $\sigma_k$  denotes the supremum of the volumes of the hyperbolic  $k$ -simplices. On the other hand, every such simplex, say  $\Delta_0^n \subset H^n$ , provides an *upper bound* on the simplicial volume of a closed hyperbolic manifold  $V$  of dimension  $n$ ,

$$\|[V]\|_{\Delta} \leq \frac{\text{vol}(V)}{\text{vol}(\Delta_0^n)}. \quad (-)$$

Ideally, one would like to prove  $(-)$  by triangulating  $V$  with all  $n$  simplices of the triangulation isometric to  $\Delta_0^n$ . The next best thing would be a triangulation of some finite covering  $\tilde{V} \rightarrow V$  into isometric copies of  $\Delta_0^n$ . In fact, it would (obviously) suffice to construct a sequence of triangulated  $i$  sheeted coverings  $\tilde{V}_i \rightarrow V$  where almost all simplices of  $\tilde{V}_i$  are nearly isometric to  $\Delta_0^n$ , where “almost” and “nearly” disappear in the limit as  $i \rightarrow \infty$ .

In general, such triangulations do not exist; nevertheless, there is a measurable “triangulation” of the fundamental class  $[V]$  into a family of simplices in  $V$  isometric to  $\Delta_0^n$ . This family is parametrized by the bundle of the orthonormal frames in  $V$ , say  $M(V)$  (which equals  $\text{Isom } H^n/\Gamma$  for  $\Gamma = \pi_1(V)$ , where we rigidly attach a frame  $m_0$  at some point  $x_0 \in \Delta_0^n$  and then moving  $m_0$  to some frame  $m = m_v \in M_v(V) \subset M(V)$  takes  $\Delta_0^n$  along to the corresponding position in  $V$ .



Thus, we have a family of simplices  $\Delta_m^n$ ,  $m \in M(V)$ , in  $V$  where each is given the orientation induced by a fixed orientation in  $V$ . (These  $\Delta_m^n \subset V$  are locally isometric to  $\Delta_0^n$  but may have self-intersections.) Our family, albeit infinite, makes an  $n$ -cycle, since every  $(n-1)$ -face is contained in the exactly two copies of  $\Delta_0^n$ , of which one is obtained from the other by the reflection in this face. What remains is to suppress squeamishness and accept this measurable cycle  $c$  for a legitimate representative of  $[V]$ , or rather of some multiple of  $[V]$ . Here,

$$\|c\|_{\Delta} = \mu(M)$$

and

$$c_{\text{mass}} = \mu(M) \text{vol}(\Delta_0^n),$$

where the measure on  $M$  descends from the Haar measure on the group  $\text{Isom } H^n$  (since  $M = \text{Isom } H^n/\Gamma$ ), and where the second equality is due to the fact that each simplex in our family  $\Gamma_m^n$  contributes *positively* to  $[V]$  being oriented according to the orientation of  $V$  defining the class  $[V]$ . In other words,

$$\|c\|_{\text{mass}}/\|c\|_\Delta = \text{vol}(\Delta_0^n),$$

and conversely,

$$\|[V]\|_\Delta \leq \sigma_n^{-1} \|c\|_{\text{mass}} = \sigma_n^{-1} \text{vol}(V) \quad (-)$$

since  $\|[V]\|_\Delta \leq \|c\|_\Delta$  by the definition of the simplicial norm of  $V$  as the inf of these over all cycles representing  $[V]$ .

Finally, adding up (+) and (-), we obtain the inequality

$$\|[V]\|_\Delta = \sigma_n^{-1} \text{vol}(V), \quad (\circ)$$

which implies (\*) by the functoriality of the norm  $\|\cdot\|_\Delta$ . (Our intuition on measurable cycles comes from the geometry of flat and almost flat manifolds. Here one clearly sees how isometric copies of a Euclidean simplex “measurably triangulate” (the fundamental class of) the flat torus  $\mathbb{T}^n$ . More generally, every manifold  $V$  with  $K(V) \leq \varepsilon^2$  can be “measurably triangulated” into roughly Euclidean simplices of size  $\approx \varepsilon^{-1}$ , where these simplices may wrap around  $V$  if the injectivity radius of  $V$  is small. Such triangulations were originally applied to the bound on the Betti numbers of  $V$ ,

$$\sum_{i=0}^n b_i \leq 2^n + \exp(\text{const}_n \varepsilon \text{diam}(V)).$$

But more interesting bounds on the homotopy invariants of  $V$  by the *volume* instead of the diameter were not practical without sufficiently many examples of manifolds with nonzero simplicial volume, which were not available prior to Thurston’s idea.

It is not very hard to analyze the case of equality in (\*): this happens if and only if the map  $f: V_1 \rightarrow V_2$  in question is homotopic to an *isometric covering*, provided  $n \geq 3$ . The easiest case here is where  $f$  is a homotopy equivalence with the conclusion equivalent to the *Mostow rigidity theorem* (see [Gro]HMTJ, [Gro–Pan]Rig, and the references therein). Probably the full Mostow rigidity for all locally symmetric spaces can be derived by a similar analysis of the equality case for the corresponding (\*)-inequality, compare [B–C–G].

**Exercise:** Prove the proportionality relation  $\|[V]\|_\Delta = c \text{vol } V$  for all compact locally homogeneous spaces  $V$ .

Finally, to get a fuller view of  $\|\cdot\|_\Delta$ , one should dualize and look at the cohomology. This shift in perspective was triggered by the challenging question put to me by P. Trauber: *Prove that the bounded cohomology of an amenable group vanishes.* This may not look very impressive, since everything “bounded” averages over “amenable” and kills cohomology without even knowing the specific definitions. (Trauber had something else up his sleeve, a conceptual proof of a theorem by Hirsch and Thurston about some affine manifolds with *non-amenable* fundamental groups.) But the idea of bounded cohomology of groups (which, I assume, is due to Trauber, compare [Johns]) proved very handy in the general framework of singular cohomology of general topological spaces  $X$ . Now one could interpret Thurston’s straightening argument as a construction of a *bounded* (because  $\text{vol } \Delta^k \leq \sigma_k < \infty$ ) cocycle in a given cohomology class of a hyperbolic manifold. In fact, such a cocycle can also be seen as a pointwise bounded,  $\Gamma$ -invariant closed  $k$ -form on the above simplex  $\Delta^\infty$  of measures on  $\Gamma$ . (This leads one to a problem of getting a clearer view on bounded (closed) forms on more general geometric models  $\mathcal{X}$  of  $X$ .)

## I<sub>+</sub> Ricci curvature beyond coverings

All applications of the condition  $\text{Ricci} \geq -\text{const}$  were reduced so far to the issuing bound on the packing type dependent on Bishop’s inequality for balls. But there is more metric information in Ricci than just a bound on the volume of balls.

**5.44. Volume growth of geodesic sectors.** A subset  $S$  in a path metric space  $V$  is called a *geodesic sector with the focal point  $v \in V$*  if it consists of a union of minimizing (geodesic) segments between the points  $s \in S$  and  $v$ . That is, for each  $s \in S$ , there is a geodesic segment between  $s$  and  $v$ . (One gets a slightly different and also useful definition by requiring *all* geodesic segments  $[v, s]$  to be in  $S$ .) We define, for such an  $S$ , the *annuli*

$$S(R_1, R_2) = \{s \in S : R_1 \leq \text{dist}(s, v) \leq R_2\},$$

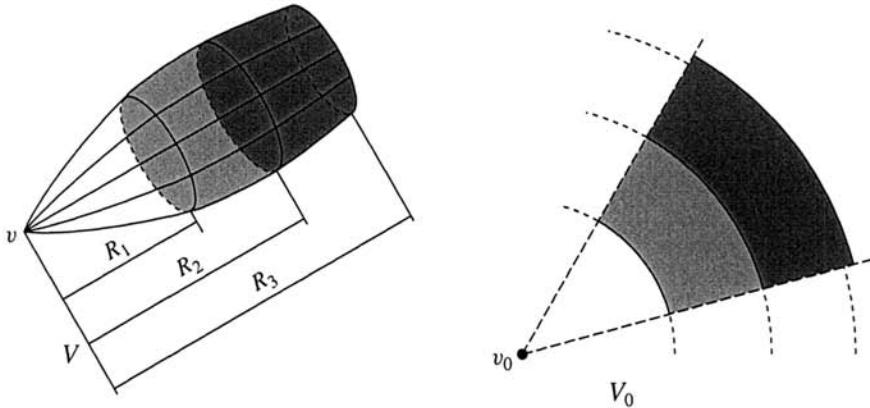
and we observe that the proof of Bishop’s theorem provides a bound on the volume of such annuli in terms of what happens in the model space  $V_0$ , which is a complete, simply connected Riemannian manifold of *constant sectional curvature*. Namely, *if  $V$  is a complete Riemannian manifold with  $\dim V_0 = \dim V$ , and  $\text{Ricci } V \geq \text{Ricci } V_0$ , then*

$$\frac{\text{vol}(S(R_2, R_3))}{\text{vol}(S(R_1, R_2))} \leq \frac{\text{vol}(A_0(R_2, R_3))}{\text{vol}(A_0(R_1, R_2))}$$

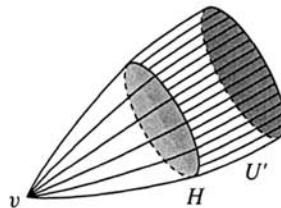
for arbitrary  $R_1 \leq R_2 \leq R_3$ , where  $A_0(R, R')$  denotes the annulus in  $V_0$ ,

$$A_0(R, R') = \{x \in V_0 : R \leq \text{dist}(x, v_0) \leq R'\}$$

for a fixed point  $v \in V_0$ .



Notice that this property (as well as the inequality for the balls) is stable under the  $\square$ -limits of mm-spaces and so could be used as an axiom of  $\text{Ricci} \geq -\text{const}$  for singular spaces (compare [Che–Col]). Also, this property allows a bound on the volume of a region  $U' \subset V$  shadowed by a hypersurface  $H$  from a point  $v \in V$ .

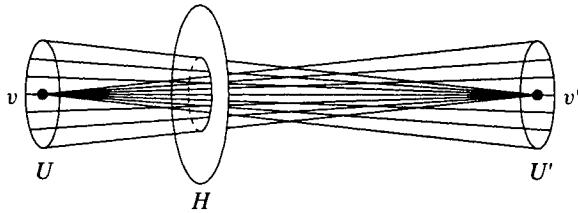


For example, if  $\text{Ricci}(V, g) \geq -(n-1)g$  (and so  $V_0$  has  $K(V_0) = -1$ ) and  $\text{diam } U' \leq 1$ , then

$$\text{vol } U' \leq \text{const}_n (\text{vol}_{n-1} H) \frac{\text{diam } U'}{\text{dist}(v_0, H)}. \quad (*)$$

This follows trivially from the above for  $R_2 \rightarrow R_1$  and  $S_2(R_1, R_2)$  degenerating to  $H$ .

Now, if we want to (and we often do) estimate the volume of a region  $U'$  bounded by a hypersurface  $H$  in  $V$ , we need a point  $v$  outside  $U'$  far away from  $H$ . It may happen that we stay at a wrong point  $v$  in  $U = V \setminus U'$  as



we observe some point  $v' \in U'$ . But then we can switch our point of view and look at  $v$  from  $v'$ , thus bounding some measure in  $U$ .

One easily proves in this way the following *Poincaré–Cheeger type isoperimetric inequality* for the above  $V$ :

*If  $V$  is divided into two domains  $U$  and  $U'$  by a closed hypersurface  $H$ , then*

$$\min(\text{vol } U, \text{vol } U') \geq \text{const}_n \text{vol}_{n-1} H.$$

In fact, a similar inequality holds for all closed manifolds with given bounds  $\text{Ricci}(g) \geq R$  and  $\text{diam } V \leq D$  and yields (by Cheeger's inequality) a lower bound on the spectrum on the Laplace operator on  $V$  (see Appendix C<sub>+</sub>).

**5.45. Volume growth of distance tubes.** A subset  $T \subset V$  is called a *distance tube* with base  $T_0 \subset V$  if, for every point  $t \in T$ , there is a segment  $[t_0, t] \subset T$  with  $t_0 \in T_0$  and such that  $\text{length}[t_0, t] = \text{dist}(t, T_0)$ . We define the annuli

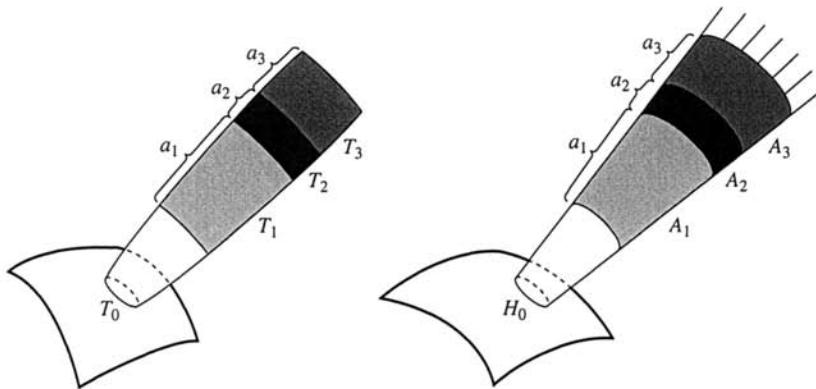
$$T(R, R+a) = \{t \in T : R \leq \text{dist}(t, T_0) \leq R+a\},$$

and we observe the following inequality for the volume of three consecutive annuli,  $T_i = T(R_i, R_{i+1})$ ,  $i = 1, 2, 3$ ,  $R_1 \leq R_2 \leq R_3 \leq R_4$ , of widths  $a_i = R_{i+1} - R_i$  relating these to the volumes of annuli  $A_i$  of the same widths in a model space  $V_0$  of constant curvature with  $\text{Ricci } V_0 \leq \text{Ricci } V$ , where the base is a hypersurface  $H_0 \subset V_0$  with all principal curvatures equal to some constant  $\kappa_0$ . (This  $H_0$  is a sphere if  $K(V_0) = \epsilon_+ > 0$ ,  $H_0$  is a sphere or a hyperplane if  $V_0 = \mathbb{R}^n$ , and it may also be a horosphere for  $K(V_0) = \epsilon_- < 0$ .)

*If  $\text{vol}(T_2)/\text{vol}(T_1) \leq \text{vol}(A_2)/\text{vol}(A_1)$ , then*

$$\frac{\text{vol } T_3}{\text{vol } T_2} \leq \frac{\text{vol } A_3}{\text{vol } A_2}, \quad (*)$$

where we assume the geodesic tube in the model space  $V_0$  is complete, i.e., contains a geodesic continuation of every geodesic segment insofar as it



remains distance-minimizing to  $H$  (while the original  $T$  does not have to be complete in this sense).

The relation  $(\star)$  is equivalent to saying that the normal equidistant deformation of smooth hypersurfaces  $H$  in  $V$  increases their mean curvature faster than it happens for  $H_0$  in  $V_0$ . This follows trivially from the definition of Ricci via the traced tube formula in 8.7 (compare [Gro]sign and the isoperimetric appendix in [Mil-Sch]). Also observe that  $(\star)$  is stable under  $\square_1$ -limits.

**Final remarks.** The inequality  $(\star)$  originates from the splitting paper by Cheeger and Gromoll, although it was known in some form to Paul Levy even earlier (compare Appendix C<sub>+</sub>). More recently, it was used by Abresch and Gromoll in their excess inequality for  $Ricci \geq -\text{const}$  (see [Abre-Grom]) followed by a flow of new remarkable development of metric geometry with  $Ricci \geq -\text{const}$  (see [Col]ARC as well as the other papers by Cheeger and Colding in our bibliography).

# Chapter 6

## Isoperimetric Inequalities and Amenability

### A. Quasiregular mappings

**6.1. Definition:** Let  $(V, g), (W, h)$  be oriented Riemannian manifolds. A mapping  $f : V \rightarrow W$  is called *quasiregular* if it is locally Lipschitz, thus differentiable almost everywhere, and if its differential  $Df_x$  and Jacobian  $J(x)$  satisfy the inequality  $0 < \|Df_x\|^n \leq c J(x)$  for almost all  $x$ , where  $c$  is a constant.

**Remark 1:** We have included the local Lipschitz hypothesis for simplicity. Some specialists (see [Mar–Ri–Vais], Def. 2.20) use a more general definition in which  $f$  is only assumed to be *ACL<sup>n</sup>*, from which they deduce that  $f$  is differentiable almost everywhere and that its Jacobian is strictly positive almost everywhere (see [Mar–Ri–Vais], Thm. 8.2).

A quasiregular mapping is called *quasiconformal* if it is a homeomorphism (cf. [Bers] for complete details).

**6.2. Examples:** Isometries and quasi-isometries are quasiregular, as are nonconstant holomorphic mappings of  $\mathbb{C}$  into a Riemann surface. If we perturb a quasiregular mapping on a compact set, then the result is again quasiregular, provided that it preserves orientation. For this reason, we are mainly interested in quasiregular mappings of *noncompact* manifolds  $V$ .

**6.3. Remark 2:** Let  $p$  be the bounded, measurable function  $V \rightarrow \mathbb{R}_+$  given by  $x \mapsto \|Df_x\|$ . The measurable tensor  $pg$  defines a length structure

on  $V$  (indeed, we can compute the lengths of many paths using the formula  $\text{length}(\gamma) = \int p(\gamma(t))\sqrt{g(\gamma'(t), \gamma'(t))} dt$ ). For this length structure, the mapping  $f: V \rightarrow (W, h)$  is quasi-isometric. Thus, a quasiregular mapping can be factored as a “conformal homeomorphism” and an arc-wise quasi-isometry whose Jacobian is positive almost everywhere, with the caveat that the intermediate space has a metric defined only a.e.

## B. Isoperimetric dimension of a manifold

**6.4. Definition:** Let  $(V, g)$  be a Riemannian manifold and  $I: \mathbb{R} \rightarrow \mathbb{R}$  an increasing function. We say that  $V$  satisfies the *isoperimetric inequality given by the function  $I$*  if there are constants  $K, K'$  such that, for each compact subset  $D$  of  $V$  with boundary, we have

$$\text{vol}(D) \leq K I(K' \text{vol}(\partial D)).$$

In particular, we say that  $V$  has isoperimetric dimension greater than  $m$  if it satisfies the isoperimetric inequality given by the function  $t \mapsto t^{m/m-1}$ . The *isoperimetric dimension* of  $V$  is then the supremum of the real  $m > 0$  such that

$$\sup_D (\text{vol}(D))^{m-1} < \infty.$$

By convention, manifolds of finite volume have zero isoperimetric dimension, and the isoperimetric dimension of no manifold lies strictly between 0 and 1. It is essential that we *not* assume that  $V$  is necessarily complete.

**6.4<sub>2+</sub> Asymptotic remark.** In what follows, we are mainly concerned with the *asymptotic* geometry of  $V$  and with the isoperimetric behavior of *large* domains  $D$  in  $V$ , say of those with  $\text{vol } D \geq 1$ . This does not disturb the picture in most cases, since small  $D$  automatically satisfy the standard Euclidean inequality under rather mild assumptions on the local geometry of  $V$ . For example, if  $V$  has *locally bounded geometry*, i.e.,  $|K(V)| \leq C^2$  and  $\text{InjRad } V \geq \rho > 0$ , then there exists a positive  $\delta = \delta(C, \rho, n = \dim V)$  such that every  $D \subset V$  with  $\text{vol } D \geq \delta$  satisfies  $\text{vol } D \leq \text{const}_n(\text{vol}(\partial D))^{n/(n-1)}$ . This follows trivially from such an inequality for  $V = \mathbb{R}^n$  by the cutting argument in Ch. 6C. Moreover, this conclusion remains valid under the milder assumptions  $\text{Ricci } V \geq -C^2$  and  $\text{vol}(B(1)) \geq \rho^n$  for the unit balls  $B(1) \subset V$  (where it is safer to assume that  $V$  is complete). This follows from the argument in Appendix C<sub>+</sub>. In fact, the manifolds  $V$  we are most interested in here are universal covers of compact manifolds, and these satisfy

$\text{vol } D \leq I(\text{vol}(\partial D))$  for some function  $I$  which is equal to  $\text{const}_V t^{n/(n-1)}$  for  $t \leq 1$  as we shall see later on.

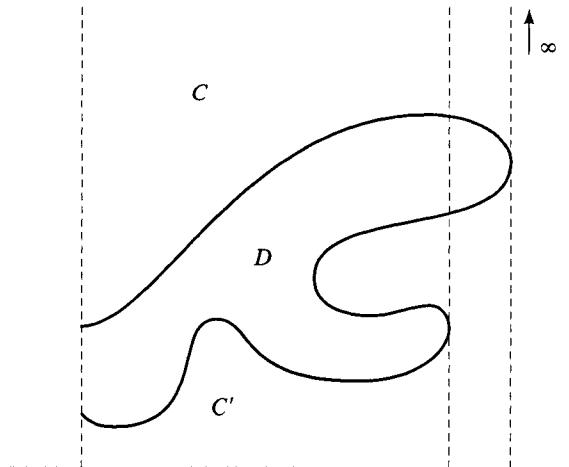
**6.5. Examples:** (a) The isoperimetric dimension of  $\mathbb{R}$  is 1, and one can easily show that the isoperimetric dimension of a product of Riemannian manifolds is the sum of the dimensions of the factor spaces. It follows that the isoperimetric dimension of  $\mathbb{R}^n$  equals  $n$ .

(b) The classical isoperimetric inequality in  $\mathbb{R}^n$  with the optimal constant  $(\text{vol}(D))^{n-1} \leq (\text{vol}(\partial D))^n / n^n \omega_n$  is more difficult but possible to obtain by using the splitting  $\mathbb{R}^n = \mathbb{R}^{n-1} \times \mathbb{R}$  and induction on  $n$  (compare [Osser], [Bur-Zalg]).

(c) If  $V$  is an open ball of radius  $r$  in  $\mathbb{R}^n$ , then  $\text{vol}(D) \leq r^{n-1} \text{vol}(\partial D)$  for each compact set  $D$  with boundary. Hyperbolic space shares the same property.

**6.6. Proposition:** *If  $A$  is a subset of  $\mathbb{H}^n$  with boundary, then*

$$\text{vol}(A) \leq \frac{1}{n-1} \text{vol}(\partial A).$$



**Proof.** Choose a point at infinity of  $\mathbb{H}^n$ . Let  $C$  be the cone formed from the segments joining this point to the points of  $A$ , and let  $C'$  be the base of the cone. Then  $A \subset C$  and  $C' \subset \partial A$ , and we will show that  $\text{vol}(C) \leq (1/n - 1) \text{vol}(C')$ . In the half-space  $x_n > 0$  of  $\mathbb{R}^n$  equipped with the metric

$\sum dx_1^2/x_n^2$ , the cone  $C$  is the set of points lying above a point of  $C'$ , and there is a function  $f$  defined on a domain  $D \subset \mathbb{R}^{n-1}$  such that

$$C = \{x_n > f(x_1, \dots, x_{n-1})\}.$$

Its graph equals  $C'$ , and we have

$$\text{vol}(C) = \int_C \frac{1}{x_n^n} dx_1 \cdots dx_n = \int_D \frac{1}{(n-1)!} f^{n-1} dx_1 \cdots dx_{n-1}$$

$$\begin{aligned} \text{vol}(C') &= \int_D [1 + (\partial_1 f)^2 + \cdots + (\partial_{n-1} f)^2]^{1/2} f^{1-n} dx_1 \cdots dx_{n-1} \\ &\geq \int f^{1-n} dx_1 \cdots dx_{n-1} = (n-1) \text{vol}(C). \end{aligned}$$

**6.7. Remark:** S.T. Yau has shown that, more generally, if  $(V, g)$  is simply connected and has sectional curvature less than  $-a^2$  for  $a > 0$ , then for every domain  $D \subset V$ , we have  $\text{vol}(D) \leq a \text{vol}(\partial D)/(n-1)$  (cf. [Yau]<sub>ICFE</sub>, p. 498, and section 8.12 of this book).

**Exercise:** Recover the proof of this property from the note [Avez] of Avez.

These examples lead us, following Sullivan [Sul]<sub>Cyc</sub>, to make the following definition:

**6.8. Definition:** A manifold  $(V, g)$  is said to be *open at infinity* if there is a constant  $C$  such that  $\text{vol}(D) \leq C \text{vol}(\partial D)$  for each domain  $D \subset V$ .

This property is *a priori* stronger than that of infinite isoperimetric dimension, since it could be the case that for each  $\alpha$  a best constant  $C(\alpha)$  such that  $\text{vol}(D) \leq C(\alpha) \text{vol}(\partial D)^{\alpha/\alpha-1}$  would satisfy  $\lim_{\alpha \rightarrow \infty} C(\alpha) = \infty$ .

**6.8<sub>2+</sub> Example.** If the fundamental group of a compact manifold is amenable without being virtually nilpotent, e.g., solvable nilpotent, then *the universal covering has infinite isoperimetric dimension* without being open at infinity. This result is due to Varopoulos, who has also shown that nonnilpotent, solvable, simply connected, unimodular Lie groups  $V$  with left-invariant Riemannian metrics satisfy

$$\text{vol } \partial D \geq C \text{vol } D / (\log \text{vol } D)^2$$

(see Ch. 6.E<sub>+</sub>).

**6.9.** The similarity in the behavior of the Euclidean disk and the hyperbolic plane suggests that the isoperimetric dimension could be a conformal invariant. This is half-true, thanks to

**Lemma (Ahlfors, cf. [Ahl] and [Osser]).** *Let  $(V, g)$  be a complete Riemannian  $n$ -manifold and assume that there is a point  $a \in V$  with*

$$\int_1^\infty \text{vol}(\partial B(a, r))^{-1/(n-1)} dr = \infty.$$

*Then the isoperimetric dimension of every metric conformally equivalent to  $g$  is  $\leq n$ .*

**Proof.** Given the metric  $f_g$ , we must show that for each  $\delta > 0$ , there is a sequence  $D_i$  of domains such that

$$\lim_{i \rightarrow \infty} \frac{\text{vol}_{f_g}(D_i)}{(\text{vol}_{f_g}(\partial D_i))^{n/(n-1)-\delta}} = \infty.$$

As we shall see, we can take the  $D_i$  to be the balls  $B(a, r_i)$  defined with respect to the metric  $g$ .

Set

$$X(r) = \text{vol}_g(B(a, r)), \quad Y(r) = \text{vol}_g(\partial B(a, r))^{n/n-1},$$

and  $A(r) = \text{vol}_g(\partial B(a, r))^{-1/n-1}$ . Since

$$X(r) = \int_{B(a, r)} f^{n/2} \nu_g = \int_0^r \left( \int_{\partial B(a, s)} f^{n/2} \nu_g \right) ds,$$

it follows from Hölder's inequality (with exponents  $n/n-1$  and  $n$ ), applied to  $f^{(n-1)/2}$  and 1, that

$$X(r) \geq \int_0^r \left( \int_{\partial B(a, s)} f^{(n-1)/2} \nu_g \right)^{n/n-1} A(s) ds = \int_0^r A(s) Y(s) ds.$$

We now show that for each  $\delta > 0$ ,  $\lim_{r \rightarrow \infty} X(r)/Y(r)^{1-\delta} = \infty$ . If this were false, then for some  $\alpha > 0$ , an inequality of the form  $X^{1+\alpha}(r) \leq CY(r)$  would hold for large  $r$ , and so by setting  $Z(r) = \int_0^r A(s)Y(s) ds$ , we would obtain the inequalities  $Z'(r) = A(r)Y(r) \geq C^{-1}Z^{1+\alpha}(r)A(r)$ . Thus,

$$-(Z^{-\alpha})'(r) = \alpha Z'(r)Z^{-1-\alpha}(r) \geq C^{-1}A(r),$$

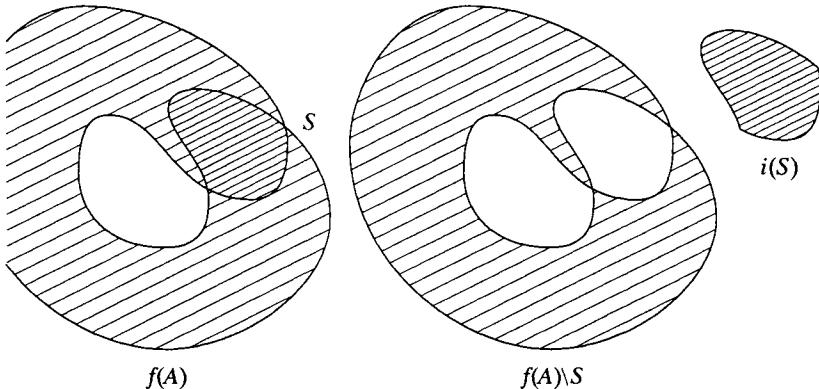
and integration on both sides gives

$$C^{-1} \int_R^\infty A(r) dr \leq Z^{-\alpha}(R) - Z^{-\alpha}(\infty),$$

contradicting the hypothesis.

To fully empower Ahlfors' lemma, it remains only to prove

**6.10. Proposition:** *If there is an arc-wise quasi-isometric map of  $V$  into a compact  $W$  whose Jacobian is a.e. positive, then the isoperimetric dimension of the universal covering  $\tilde{V}$  of  $V$  is greater than or equal to that of  $\tilde{W}$ , provided that  $\tilde{W}$  is noncompact.*



**Proof.** Let  $m$  be a real number strictly smaller than the isoperimetric dimension of  $W$ . Then, for each compact subset  $B \subset W$  with boundary, we have  $\text{vol}(B) \leq \text{const}(\text{vol}(B))^{m/m-1}$ . If  $f: V \rightarrow W$  is an arc-wise quasi-isometry and  $A \subset V$  is a compact set with boundary, then the set  $f(A)$  is not always a compact set with boundary in  $W$ , but since  $f$  has a.e. positive Jacobian, the only phenomenon that could result in this happening is an “overlap” (see figure above). Using an isometry  $i$  of  $\tilde{W}$  (of which there are many, since  $W$  is compact whereas  $\tilde{W}$  is not) it is possible to move the self-intersection  $S$  a bit further, to apply the isoperimetric inequality to  $f(A) \setminus S \cup i(S)$ , and to conclude  $\text{vol}(f(A)) \leq \text{const}(\text{vol}(f(\partial A)))^{m/m-1}$ . Since for a.e.  $x \in V$ ,

$$\|Df_x\| \leq c \quad \text{it follows that} \quad \text{vol}(f(\partial A)) \leq c^{\dim(V)} \text{vol}(\partial A)$$

$$\|Df_x^{-1}\| \leq c^{-1} \quad \text{it follows that} \quad \text{vol}(f(\partial A)) \geq c^{-\dim(V)} \text{vol}(A),$$

and thus  $V$  satisfies the isoperimetric inequality

$$\text{vol}(A) \leq \text{const}(\text{vol}(\partial A))^{m/m-1}.$$

We conclude that  $V$  has isoperimetric dimension greater than  $m$ .

The fundamental consequence of these results that will be used throughout the remainder of the chapter is the following:

**6.11. Corollary:** *Let  $(V_1, g_1), (V_2, g_2)$  be Riemannian manifolds such that the former has dimension  $n$  and satisfies the hypotheses of Ahlfors' lemma and the latter has isoperimetric dimension strictly greater than  $n$ . Then there is no quasiregular map from  $(V_1, g_1)$  into  $(V_2, g_2)$ .*

**Proof.** If there were such a map, then by Proposition 6.10 and Remark 6.3, the manifolds  $(V_1, pg_1)$  — for some function  $p$  — and  $(V_2, g_2)$  would satisfy isoperimetric inequalities with the same exponent.

**6.12. Examples:** The preceding hypotheses are satisfied if  $(V_1, g_1)$  is Euclidean space or a compact manifold with finite volume and if  $(V_2, g_2)$  is open at infinity.

In particular, by taking  $V_1$  to be the complex plane and  $V_2$  as the unit disk, we recover Liouville's theorem: "Every bounded entire function on  $\mathbb{C}$  is constant." In fact, we have a more general version that applies to quasiconformal maps as well as conformal maps and uses no complex analysis.

Similarly, in anticipation of the remainder of the chapter, which is devoted to the computation of isoperimetric dimension, we can set  $V_1 = \mathbb{C}$  and  $V_2 = S^2 \setminus \{a, b, c\}$ , for distinct  $a, b, c$  to obtain a quasiconformal version of the celebrated Picard theorem (cf. [Rudin]): "Every entire function on  $\mathbb{C}$  which omits two values is constant." Our version of this theorem can, furthermore, be generalized to higher dimensions by taking  $V_1 = \mathbb{R}^3$  and  $V_2 = S^2 \setminus N$ , where  $N$  is a nontrivial knot.

## C. Computations of isoperimetric dimension

**6.13.** In this section, we will show that if  $V_2$  is the universal cover of a compact Riemannian manifold  $V$ , then the existence of an isoperimetric inequality for  $V_2$  depends only on the structure of the fundamental group of  $V$ . We must therefore introduce the notion of an isoperimetric inequality in a discrete group of finite type.

**6.14. Definition:** Let  $\Gamma$  be a group with a finite system of generators  $\gamma_1, \dots, \gamma_p$ , and let  $\|\cdot\|$  be the algebraic (word) norm associated with this system (see 3.20). The *boundary* of a subset  $A \subset \Gamma$  is defined as the set

$$\partial A = \{x \in A : \exists y \notin A \text{ with } \|yx^{-1}\| \leq 1\}.$$

If  $I : \mathbb{R}_+ \rightarrow \mathbb{R}_+$  is an increasing function, then we say that  $\Gamma$  satisfies the *isoperimetric inequality given by  $I$*  if there exist constants  $K, K'$  such that,

for each finite subset  $A \subset \Gamma$ , we have

$$\text{card}(A) \leq K I(K' \text{card}(\partial A)).$$

In particular,  $\Gamma$  has isoperimetric dimension greater than  $m$  if  $\Gamma$  satisfies the isoperimetric inequality given by the function  $I(t) = t^{m/m-1}$ .

The group  $\Gamma$  is called *amenable* if it does not satisfy the isoperimetric inequality given by the function  $t \mapsto t$ .

In other words, a non-amenable group is the counterpart of a manifold that is open at infinity (see [Gre]).

**6.15. Remark 1:** The notion of boundary for subsets of  $\Gamma$  depends on the choice of generators, but the number of elements in the boundary is at worst multiplied by a constant when a different set of generators is chosen. It follows that the notion of isoperimetric inequality and related ideas do not depend on the choice of generating set, provided that it is finite.

**6.16. Remark 2:** Any non-amenable group must have exponential growth. Indeed, if  $B(R) = \{x \in \Gamma : \|x\| \leq R\}$ , then by hypothesis there is a constant  $c$  such that  $\text{card}(B(R)) = N(R) \leq c \text{card}(\partial B(R))$ , but  $\partial B(R) \subset B(R) \setminus B(R-1)$ , and so  $N(R) \geq (c/c-1)N(R-1)$ , hence  $N(R) \geq (c/c-1)^R$ . The converse is false in general: Solvable groups without nilpotent subgroups of finite index are amenable and have exponential growth (see [Wolf]<sub>Gro</sub>, Thm. 4.8).

The following general lemma provides the best means for showing that a group is non-amenable.

**6.17. Lemma:** *Let  $\Gamma$  be a group of finite type equipped with the algebraic norm associated with a finite system of generators. Suppose that there is a mapping  $f: \Gamma \rightarrow \Gamma$  such that, for each  $x \in \Gamma$  we have i)  $\|f(x)x^{-1}\| \leq 1$  and ii)  $f^{-1}(x)$  contains at least two elements. Then  $\Gamma$  is non-amenable.*

**Remark:** The same conclusion holds if we replace “1” in condition (i) by an arbitrary constant  $K$  (taking  $\{x : \|x\| \leq K\}$  as a new set of generators).

**Proof.** Given a finite subset  $A \subset \Gamma$ , set  $A' = A \setminus \partial A$ . If  $x \in \Gamma \setminus A$  and  $f(x) \in A$ , then  $f(x) \in \partial A$ , since  $\|f(x)x^{-1}\| \leq 1$ , and thus  $f(x) \notin A'$ . In other words,  $f^{-1}(A') \subset A$ ; thus by (2),  $\text{card}(f^{-1}(A')) \geq 2 \text{card}(A')$  so that  $\text{card}(A') \leq \text{card}(A)/2$  and so  $\text{card}(A) \leq 2 \text{card}(\partial A)$ .

**6.17<sub>2+</sub> Exercise:** Prove the converse: every non-amenable, finitely generated group  $\Gamma$  admits a self-mapping  $f: \Gamma \rightarrow \Gamma$  such that  $\text{card } f^{-1}(x) \geq 2$  for all  $x \in \Gamma$  and  $\|f(x)x^{-1}\| \leq \text{const} = \text{const}_\Gamma$ . (*Hint:* Show as a warm-up that

every oriented manifold  $V$  open at infinity admits a *bounded*  $(n - 1)$ -form  $\eta$  with  $d\eta = (\text{the volume form of } V)$ . This follows from the Hahn–Banach theorem and/or from Whitney-type duality between mass and comass, see Ch. 4.D. Then pass from  $(n - 1)$ -forms to vector fields and from these to self-mappings.)

**6.18. Corollary:** *A free group having at least two generators is non-amenable.*

**Proof.** Indeed, the map  $f$  that erases the last letter of each word suffices.

**Remark:** A group containing a non-amenable subgroup is non amenable.

**6.19. Theorem:** *The fundamental group and the universal cover of a compact Riemannian manifold  $V$  satisfy the same isoperimetric inequality.*

**Sketch of the proof.** Let  $\tilde{V}$  denote the universal cover of  $V$  and  $\Delta$  a fundamental domain for the action of  $\Gamma = \pi_1(V)$  on  $\tilde{V}$ . Suppose that  $\Gamma$  satisfies the isoperimetric inequality given by a function  $I: \mathbb{R}_+ \rightarrow \mathbb{R}_+$ . We first show (Lemma 1 below) that the isoperimetric inequality given by  $I$  for sets of the form  $\bigcup_{\gamma \in B} \gamma\Delta$  follows immediately, and conversely, an inequality satisfied by  $\tilde{V}$  is also satisfied by  $\Gamma$ . If  $A$  is now an arbitrary submanifold of  $V$  with boundary, then Lemmas 2 and 3 enable us to compare, for each  $\gamma \in \Gamma$ ,  $A \cap \gamma\Delta$  and  $\partial(A \cap \gamma\Delta)$ , and so to compare  $A$  and  $\partial A$  to a union of translates of  $\Delta$ .

**6.20. Lemma 0:** *There exist regular fundamental domains.*

**Proof.** Given a smooth triangulation of  $V$ , it is possible to choose disjoint liftings of each simplex of maximal dimension, thus providing a fundamental domain  $\Delta$  (it is unimportant that  $\Delta$  is not connected). The notions of volume for  $\Delta$  and its boundary then make sense.

**6.21. Lemma 1:** *If  $\tilde{V}$  satisfies an isoperimetric inequality, then the same is true for  $\Gamma$ . Conversely, if  $\Gamma$  satisfies the isoperimetric inequality given by a function  $I$ , then subsets of  $\tilde{V}$  of the form  $A = \bigcup_{\gamma \in B} \gamma\Delta$  satisfy  $\text{vol}(A) \leq KI(K' \text{vol}(\partial A))$  for some constants  $K, K'$ .*

**Proof.** First we construct a good set of generators for  $\Gamma$ , setting

$$S = \{\gamma \in \Gamma \setminus \{1\} : \gamma\Delta \text{ and } \Delta \text{ share a common } (n - 1)\text{-face}\}.$$

Note that  $S' = \{\gamma \in \Gamma \setminus \{1\} : \gamma\Delta \cap \Delta \neq \emptyset\}$  generates  $\Gamma$ . Indeed, since  $\Gamma$  acts properly on  $\tilde{V}$ , it follows that for each  $x \in \tilde{V}$  the set  $\{\gamma \in \Gamma : B(x, 1) \cap \gamma \neq \emptyset\}$

is finite, and so

$$r = \inf\{d(x, \gamma\Delta) : \gamma \in \Gamma, x \notin \gamma\Delta\} > 0,$$

and  $B(x, r/2)$  only intersects  $\gamma\Delta$  if  $x \in \gamma\Delta$ , i.e.,  $\gamma\Delta \cap \Delta \neq \emptyset$  for  $\gamma \in S'$ . It follows that  $B(x, r/2) \subset S'\Delta$  and, if  $G'$  is the group generated by  $S'$ , that  $G'\Delta$  contains its  $(r/2)$  neighborhood and is therefore open and closed. Since  $\tilde{V}$  is connected, we have  $G'\Delta = \tilde{V}$ , and so  $G' = \Gamma$ . It suffices to show that the subgroup  $G$  generated by  $S$  contains  $S'$ . Let  $\gamma \in S'$  and  $x \in \Delta \cap \gamma\Delta$ . There exist points  $x_1 \in \Delta$  and  $x_2 \in \gamma\Delta$  very close to  $x$ . If  $c$  is a path joining  $x_1, x_2$ , we can assume by transversality that  $c$  does not intersect any codimension-2 face of the translates of  $\Delta$ . Thus,  $c$  moves successively across the translates  $\Delta, \gamma_1\Delta, \dots, \gamma_k\Delta, \gamma\Delta$  by passing through a common  $(n-1)$ -face of  $\Delta$  and  $\gamma_1\Delta$ , a common  $(n-1)$ -face of  $\gamma_1\Delta$  and  $\gamma_2\Delta$ , etc..., which implies that  $\gamma_1, \gamma_2\gamma_1^{-1}, \dots, \gamma\gamma_k^{-1} \in S$ , and thus  $\gamma \in G$ .

Let  $A = \bigcup_{\gamma \in B} \gamma\Delta$ . It is easy to check that for  $\gamma \in B$ ,

$$\begin{aligned} & \{\gamma\Delta \text{ and } \partial A \text{ have an } (n-1)\text{-face in common}\} \\ & \Leftrightarrow \{\exists \gamma' : \|\gamma'\| = 1 \text{ and } \gamma'\gamma\Delta \not\subset A\} \\ & \Leftrightarrow \{\gamma \in \partial B\}. \end{aligned}$$

Set  $K^{-1} = \min\{\text{vol}(\Delta \cap \gamma\Delta) : \gamma \in S\}$ . Then

$$\begin{aligned} \text{vol}(\partial A) &\leq \text{vol}(\partial\Delta) \cdot \text{card}\{\gamma \in B : \gamma\Delta \text{ and } \partial A \\ &\quad \text{have a common } (n-1)\text{-face}\} \\ &= \text{vol}(\partial\Delta) \text{ card}(\partial B); \end{aligned}$$

$$\begin{aligned} \text{vol}(\partial A) &\geq K^{-1} \text{ card}\{\gamma \in B : \gamma\Delta \text{ and } \partial A \text{ have a common } (n-1)\text{-face}\} \\ &= K^{-1} \text{ card}(\partial B); \end{aligned}$$

$$\text{vol}(A) = \text{vol}(\Delta) \text{ card}(B).$$

In conclusion,

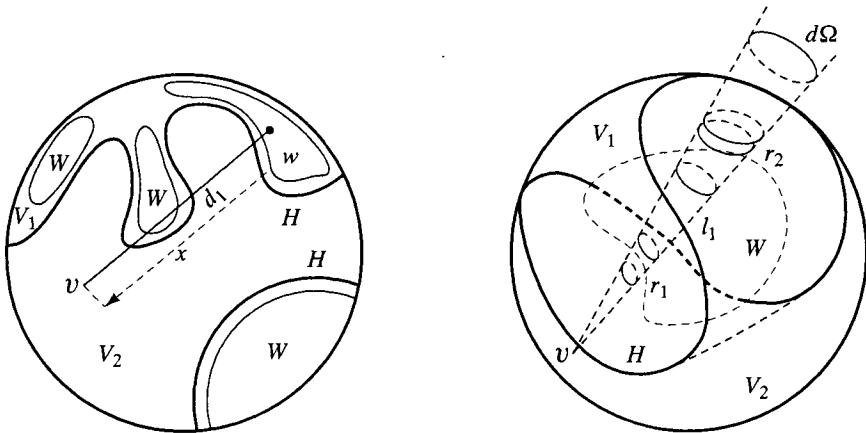
If  $\text{card}(B) \leq I(\text{card}(\partial B))$ , then  $\text{vol}(A) \leq \text{vol}(\Delta)I(K \text{ vol}(\partial A))$ ,

If  $\text{vol}(A) \leq I(\text{vol}(\partial A))$ , then  $\text{card}(B) \leq (\text{vol}(\Delta))^{-1}I(\text{vol}(\partial\Delta) \text{ card}(\partial B))$ .

Let  $B^n$  be the standard  $n$ -ball,  $V_1, V_2$  two disjoint (not necessarily connected) open sets in  $B^n$  whose common boundary consists of a hypersurface  $H$  and such that  $B^n = V_1 \cup V_2 \cup H$ . We assume  $\text{vol}(V_1) \leq \text{vol}(V_2)$ .

**6.22. Lemma 2:**  $\text{vol}(V_1) \leq 2^{n+1} \text{ vol}(H)$ .

**Proof.** We construct a subset  $W \subset V_1$  and a point  $v \in V_2$  such that



(i)  $\text{vol}(W) > \text{vol}(V_1)/2$ .

(ii) If  $w \in W$  and if  $d_v(w)$  is the distance between  $v$  and the last intersection of the segment  $[v, w]$  with  $H$ , then  $d_v(w) \geq d(v, w)/2$ .

Set

$$U = \left\{ (v, w) \in V_2 \times V_1 : d_v(w)/d(v, w) \geq \frac{1}{2} \right\}$$

$$T = \left\{ (w, v) \in V_1 \times V_2 : d_w(v)/d(v, w) \geq \frac{1}{2} \right\}$$

and define  $i : V_2 \times V_1 \rightarrow V_1 \times V_2$  by  $i(v, w) = (w, v)$ . Note that  $d_v(w) + d_w(v) \geq d(v, w)$ , and so  $\{d_v(w) \leq d(v, w)/2\}$  implies  $\{d_w(v) \geq d(v, w)/2\}$ , i.e.,

$$U^c \subset \left\{ (v, w) \in V_2 \times V_1 : d_w(v)/d(v, w) \geq \frac{1}{2} \right\}$$

and  $i(U^c) \subset T$ . We conclude that

$$\text{vol}(U) + \text{vol}(T) \geq \text{vol}(U) + \text{vol}(i(U^c)) = \text{vol}(U) + \text{vol}(U^c) = \text{vol}(V_2 \times V_1),$$

and one of the two volumes is  $\geq \text{vol}(V_1 \times V_2)/2$ .

Suppose that  $\text{vol}(U) \geq \text{vol}(V_2 \times V_1)/2$ . Since  $\text{vol}(U) = \int_{V_2} \text{vol}(U_v) dv$ , the number

$$\int_{V_2} \left( \text{vol}(U_v) - \frac{1}{2} \text{vol}(V_1) \right) dv$$

is positive, where

$$U_v = \left\{ w \in V_1 : d_v(w) \geq \frac{1}{2} \right\}.$$

Thus, the integrand is not always strictly negative; in other words, there exists  $v \in V_2$  such that  $\text{vol}(U_v) \geq \text{vol}(V_1)/2$ , and we take  $W = U_v$ . Now we must find an upper bound for the volume of  $W$  as a function of the volume of  $H$ . Let  $d\Omega$  be the volume form on the sphere of center  $v$  and radius 1. In spherical coordinates centered at  $v$ , at the distance  $r$  from  $v$ , the volume element of  $B^n$  is  $r^{n-1} dr d\Omega$ . Almost every ray intersects  $H$  transversely at a finite number of points  $r_1, \dots, r_k$ . Let  $I_i$  be the part of the ray within  $W$  lying between  $r_i$  and  $r_{i+1}$ . The volume element of  $W$  within the cone  $d\Omega$  is

$$dW = d\Omega \sum_{i=1}^k \int_{I_i} r^{n-1} dr.$$

By Property (ii) of  $W$ , however,  $r \geq 2d_V$ , and, for a point of  $I_i$ , we have  $d_V = r_i$ , thus

$$dW \leq d\Omega \sum_{i=1}^k (2r_i)^{n-1} \int_{I_i} dr \leq 2^n \sum_{i=1}^k r_i^{n-1} d\Omega \leq 2^n ds,$$

the volume element of  $H$  lying in the cone  $d\Omega$ .

We conclude that  $\text{vol}(W) \leq 2^n \text{vol}(H)$  and  $\text{vol}(V_1) \leq 2^{n+1} \text{vol}(H)$ . In the case when  $\text{vol}(T) \geq \text{vol}(V_2 \times V_1)/2$ , the same argument gives the inequality  $\text{vol}(V_2) \leq 2^{n+1} \text{vol}(H)$ , which provides the desired result.

**6.23. Lemma 3:** *If we define  $\partial_1 V = \partial V \setminus \{H\}$ , then*

$$\text{vol}(\partial_1 V) \leq n2^{n+2} \text{vol}(H).$$

**Proof.** For  $x \in \partial_1 V$ , we denote by  $r(x)$  the distance from the origin to the first point of  $H$  along the ray issuing from  $x$ . Let  $\alpha$  be the angle between the ray and the normal to  $H$  at this point. In this notation, we have

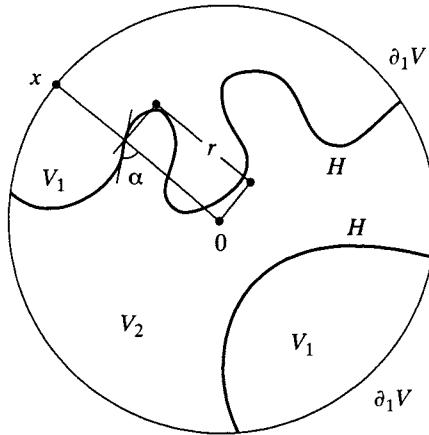
$$\text{vol}(H) \geq \int_{\partial_1 V} \frac{r^{n-1}}{\cos(\alpha)} d\Omega \geq \int_{\partial_1 V} r^{n-1} d\Omega.$$

However,

$$\text{vol}(V_1) \geq \int_{\partial_1 V} \left( \int_r^1 s^{n-1} ds \right) d\Omega = \int_{\partial_1 V} \frac{1-r^n}{n} d\Omega,$$

and so

$$n \text{vol}(V_1) \geq \text{vol}(\partial_1 V) - \int_{\partial_1 V} r^n d\Omega \geq \text{vol}(\partial_1 V) - \text{vol}(H).$$



Since  $\text{vol}(V_1) \leq 2^{n+1} \text{vol}(H)$  by Lemma 2, it follows that  $\text{vol}(\partial_1 V) \leq (n2^{n+1} + 1) \text{vol}(H)$ , and so

$$\text{vol}(\partial_1 V) \leq n2^{n+2} \text{vol}(H).$$

**6.24. End of the proof of Theorem 6.19.** Note that the fundamental domain  $\Delta$  constructed in Lemma 0 is the union of a finite number of simplices  $\Delta_1, \dots, \Delta_p$ , each of which is the image of a ball under a quasi-isometric homeomorphism. Thus, Lemmas 2 and 3 are true for each  $\Delta_i$  with the constants  $c_2, c_3$ .

Given a submanifold  $A \subset \tilde{V}$  with boundary, we denote by  $A'$  the union of the translates of the  $\Delta_i$ , at least half of which are contained in  $A$ , i.e.,

$$A' = \bigcup_{i=1}^p \bigcup_{\gamma \in \Gamma} \left\{ \gamma \Delta_i : \text{vol}(\gamma \Delta_i \cap A) \geq \frac{1}{2} \text{vol}(\Delta_i) \right\}.$$

The sets  $A, \partial A$  are divided between  $\tilde{V} \setminus A'$  and  $A'$  into  $A_1, A_2$  and  $\partial_1 A, \partial_2 A$ . Similarly,  $\partial A'$  splits between  $A$  and  $\tilde{V} \setminus A'$  into  $\partial_1 A$  and  $\partial_2 A'$ , which satisfy

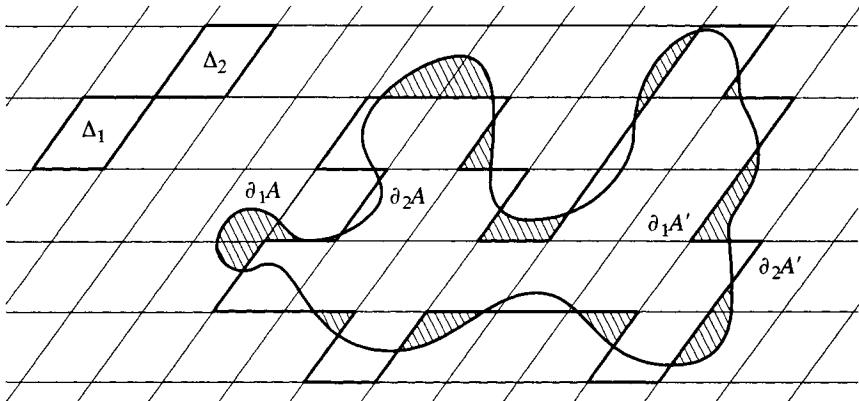
$$\text{vol}(\partial_1 A') \leq c_3 \text{vol}(\partial_1 A) \quad \text{and} \quad \text{vol}(\partial_2 A') \leq c_3 \text{vol}(\partial_2 A),$$

so that

$$\text{vol}(\partial A') \leq c_3 \text{vol}(\partial A)$$

$$\text{vol}(A_1) \leq c_2 \text{vol}(\partial_1 A) \leq c_2 \text{vol}(\partial A) \quad \text{and} \quad \text{vol}(A_2) \leq \text{vol}(A').$$

If  $\Gamma$  satisfies the isoperimetric inequality given by the function  $I$ , then Lemma 1 implies  $\text{vol}(A') \leq KI(K' \text{vol}(\partial A'))$  and so, since  $\text{vol}(A) \leq \text{vol}(A') +$



$$c_2 \operatorname{vol}(\partial A),$$

$$\operatorname{vol}(A) \leq K I(K' c_3 \operatorname{vol}(A)) + c_2 \operatorname{vol}(\partial A) \leq K'' I(K''' \operatorname{vol}(\partial A)),$$

when  $I$  increases at least linearly, which is necessarily the case, for example, when  $I$  is an exponential function.

### Examples:

**6.25.** The group  $\mathbb{Z}^n$  has isoperimetric dimension  $n$ , since it is the fundamental group of a compact Riemannian manifold (flat torus) whose universal cover  $\mathbb{R}^n$  has isoperimetric dimension  $n$ .

**6.26.** The fundamental group of a compact hyperbolic manifold is non-amenable, since the universal cover  $\mathbb{H}^n$  is open at infinity. The same is true of the fundamental group of a compact, nonflat manifold with nonpositive sectional curvature, as follows from [Avez].

On the other hand, if  $V$  is simply connected, has  $K(V) \leq 0$ , and its Ricci curvature satisfies  $\operatorname{Ricci}(g) \leq -\varepsilon g$  for some  $\varepsilon > 0$ , then  $V$  is open at infinity.

**6.27. Conjecture:** In fact, “nonpositive sectional curvature and strictly negative scalar curvature” should be sufficient.

**6.28.** Using only the hypothesis of nonpositive sectional curvature, D. Hoffman and J. Spruck have succeeded in proving that the isoperimetric dimension of  $V$  is greater than  $n$  (see [Osser], p. 1214, and [Hoff–Spru]).

**Conjecture:** *Under these hypotheses, we have the same inequality and the same constant as for Euclidean space.* This is known to be true for products

of surfaces and manifolds of constant curvature.

**6.28<sub>+</sub>**. This conjecture has been solved in dimension 4 by Croke (see [Croke]<sub>4DII</sub>) and for dimension 3 by Kleiner (see [Kle]). Consequently, it holds true for Cartesian products of these manifolds (we suggest that the reader actually work out the proof of the stability of the *sharp* Euclidean isoperimetric inequality under cartesian products). But the *sharp* isoperimetric inequality for general (complete, simply connected) manifolds  $V$  with  $K \leq 0$  still remains conjectural for  $\dim V \geq 5$ , where “sharp” refers to the constant  $C_n$  in  $\text{vol } D \leq C_n(\text{vol } \partial D)^{n/(n-1)}$ , which is supposed to make this an equality for the Euclidean balls  $D$ . In fact, one expects even sharper results for particular classes of manifolds with  $K(V) \leq 0$ . For example, one wants to know the sharp inequality in symmetric spaces  $V$  (where it is unknown even for  $\mathbb{R}\text{-rank } V = 1$ ), and one expects an isoperimetric comparison theorem between manifolds  $V$  with  $K(V) \leq 0$  and  $\text{Ricci } V \leq -(n-1)$  and those with  $K = -1$ .

On the other hand, the non-sharp isoperimetric inequality of Hoffman and Spruck admits the following generalization (see p. 143 in [Gro]FRM).

*Let  $V$  be a complete Riemannian manifold where every  $(k-1)$  dimensional cycle  $Y$  can be filled in by a  $k$ -chain  $Z$  such that*

$$\text{vol}_k Z \leq C(\text{vol}_{k-1} Y)(\text{diam } Y) \quad (*)$$

*for a given  $C > 0$  and  $k = 1, 2, \dots, m$ . Then every such  $Y$  can be filled in by  $Z$  satisfying*

$$\text{vol}_k Z \leq C'(\text{vol}_k Y)^{k/(k-1)}, \quad (**)$$

*where  $C' = C'(C, m)$ .*

*In particular, if  $m = n = \dim V$ , then the inequality  $(*)$  for all  $k \leq n$  implies the ordinary isoperimetric inequality for domains  $D \subset V$ .*

**Remarks:** (a) In order to have  $(**)$ , it is sufficient to prove  $(*)$  only for “round” cycles  $Y$ , where  $\text{diam}(Y) \leq C_0(\text{vol } Y)^{1/(k-1)}$  (see [Gro]FRM).

(b) The sharp filling inequality  $(**)$  is known for  $V = \mathbb{R}^n$  from the work of Almgren (see [Alm]<sub>Opt</sub>).

(c) The inequality  $(*)$  (obviously) holds true for  $K(V) \leq 0$  and, more generally, if  $V$  has *no focal points*. Additionally, it is likely that “no conjugate points” would be enough for  $(**)$  (compare [Gro]FRM).

**6.29<sub>+</sub> Varopoulos’ theorem:** *A discrete, finitely generated group of finite type whose isoperimetric dimension is finite contains a nilpotent subgroup*

of finite index. This was conjectured for solvable groups in the French edition of this book and proven by Varopoulos in full generality, see 6.E<sub>+</sub>.

**6.30. Remark:** More precise results have been obtained for local homeomorphisms using *conformal moduli* of families of curves.

**Theorem (Zoritch, see [Zor] or [Laur–Belin]):** *Let  $V_1, V_2$  be Riemannian manifolds of the same dimension  $> 3$ , and suppose that the fundamental group of  $V_1$  is  $\mathbb{Z}^n$  whereas  $V_2$  is simply connected. If there is a quasiregular local homeomorphism  $f : \tilde{V}_1 \rightarrow V_2$ , then  $f$  is necessarily a homeomorphism of  $\tilde{V}_1$  onto an open subset of  $V_2$  whose complement has dimension 0.*

**Theorem:** *The same conclusion is true if  $\tilde{V}_1$  is a Riemannian manifold that satisfies the hypothesis of Ahlfors' lemma, Lemma 6.9 (compare [Zor–Kes]).*

**6.31. Corollary:** *When  $\tilde{V}_1 = \mathbb{R}^n$ , then since homeomorphisms preserve ends (see [Bour]), and since  $\mathbb{R}^n$  has only one end, the set  $V_2 \setminus f(\tilde{V}_1)$  contains at most one point. Consequently, if  $V_2$  is a simply connected manifold other than  $\mathbb{R}^n$  and  $S^n$ , there is no quasiregular local homeomorphism  $\mathbb{R}^n \rightarrow V_2$ .*

## D. Generalized quasiconformality

**6.32.** We are now tempted to define quasiregular mappings between manifolds of unequal dimensions.

There is a notion of a  $q$ -dimensional isoperimetric inequality within a Riemannian  $n$ -manifold where  $n > q$  as follows: Given an increasing function  $I : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ , the manifold  $V$  satisfies the  $q$ -dimensional isometric inequality given by the function  $I = I(t)$  if, for every  $q$ -manifold  $S$  with boundary and for every map  $f : \partial S \rightarrow V$ , there is an extension of  $f$  to  $S$  such that  $\text{vol}(f(S)) \leq KI(K' \text{vol}(f(\partial S)))$  for two constants  $K, K'$ .

For example, if, for each closed curve  $c$  of length  $\ell$  in  $V$ , there exists an extension of  $c$  to a disk having area  $\leq \text{const}(\ell^{p/p_1})$ , then we say that  $V$  has *2-dimensional isoperimetric rank greater than  $p$* . (Here, “rank” replaces “dimension,” since the latter sounds awful here.)

**6.33. Proposition:** *Euclidean space has 2-dimensional isoperimetric rank equal to 2. Hyperbolic space has infinite 2-dimensional isoperimetric rank.*

**Proof.** Let  $c$  be a closed, connected curve of length  $\ell$  in  $\mathbb{R}^n$  and  $O$  a point of  $c$ . The cone  $K$  on  $c$  of origin  $O$  is an extension of  $c: S^1 \rightarrow \mathbb{R}^n$  to

$$B^2 = \{re^{it} : 0 \leq r \leq 1, 0 \leq t \leq 2\pi\},$$

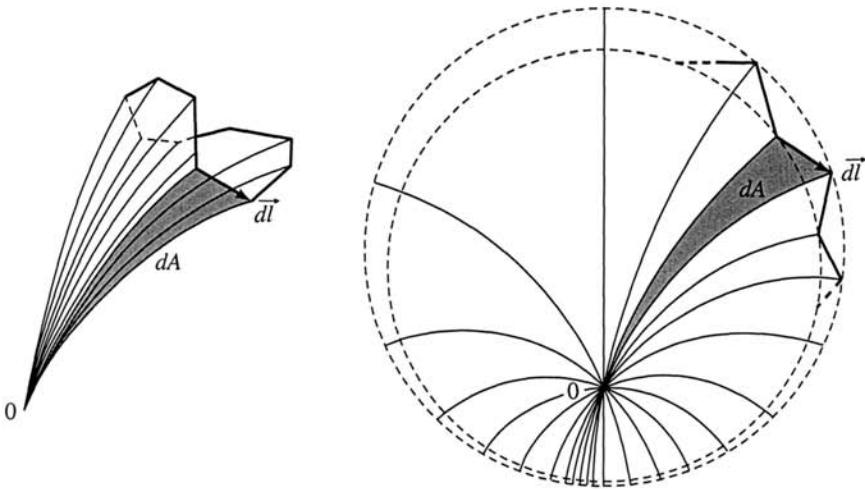
given by  $re^{it} \mapsto K(re^{it}) = K(r, t) = O + rO(c(t))$ . The area of  $K$  is

$$\begin{aligned} \int_0^{2\pi} dt \int_0^1 \left\| \frac{dK}{dr} \wedge \frac{dK}{dt} \right\| dr &\leq \int_0^{2\pi} dt \int_0^1 \|Oc(t)\| \|c'(t)\| r dr \\ &\leq \frac{\ell}{4} \int_0^{2\pi} \|c'(t)\| dt \leq \frac{\ell^2}{4}. \end{aligned}$$

Thus, Euclidean space satisfies the inequality

$$\text{vol}(K) \leq \frac{1}{4} \text{vol}(C)^2.$$

Given a curve  $c$  of length  $\ell$  in  $\mathbb{H}^n$ , choose a point  $O$  of  $\mathbb{H}^n$  lying at a large distance from  $c$ . The length element  $d\ell$  on  $c$  determines an area element  $dA$  on the cone  $K$  with vertex  $O$  based at  $c$ .



We map  $dA$  onto the hyperbolic plane  $\mathbb{H}^2$  and attach  $N$  isometric triangles to  $dA$ , in such a way to approximately cover a domain  $D \subset \mathbb{H}^2$  whose boundary  $\partial D$  consists of  $N$  small mutually isometric segments in  $\mathbb{H}^2$  (Proposition 6.6)  $\text{Area}(D) \leq \text{length}(\partial D)$ , i.e.,  $N dA \leq N d\ell$ . We conclude that

$$\text{Area}(K) = \int_c dA \leq \int_c d\ell = \ell.$$

**6.33.bis.** If  $V^n$  is simply connected and has nonpositive sectional curvature, then the  $q$ -dimensional isoperimetric rank of  $V$  is greater than  $n$  for  $q < n = \dim(V)$  (see [Hoff–Spru]).

An argument analogous to that of Lemma 6.9 enables us to define the notion of  $q$ -dimensional isoperimetric rank for a group  $\Gamma$ , provided that  $\Gamma$  admits a discrete cocompact action on a manifold  $\tilde{V}$  with trivial homotopy groups in dimensions  $< q$ , i.e.,  $\pi_1(\tilde{V}) = 0, \pi_2(\tilde{V}) = 0, \dots, \pi_{q1}(\tilde{V}) = 0$ . In particular, we have the following

**6.34. Proposition-Definition:** If  $V$  is a compact manifold with  $\pi_i(V) = 0$  for  $i = 2, \dots, q-1$ , then its fundamental group and universal cover satisfy the same  $q$ -dimensional isoperimetric inequalities.

**Corollary:** *The universal cover of a compact manifold whose fundamental group is isomorphic to that of a hyperbolic manifold has infinite 2-dimensional isoperimetric rank.*

**6.34<sub>2+</sub><sup>1</sup> Remarks.** (a) Two dimensional isoperimetric inequalities make sense for all finitely generated groups  $\Gamma$ , where they measure the number of elementary steps needed to transform a word representing the identity element in  $\Gamma$  to the trivial word. For example,  $\Gamma$  has the *solvable word problem* if and only if the universal covering  $\tilde{V}$  of  $V$  with  $\pi_1(V) = \Gamma$  satisfies the 2-dimensional isoperimetric inequality with a *subrecursive* function  $I$ , which means that  $\text{ent } I(\text{ent } t)$  is recursive, with “ent” standing for “integral part” (compare 7.8<sub>2</sub><sup>1</sup> and the references therein).

(b) If a group  $\Gamma$  (or a reasonable space) satisfies the *subquadratic* 2-dimensional inequality, i.e., where  $I(t)/t^2 \rightarrow 0$  for  $t \rightarrow \infty$  (which corresponds to 2-dimensional rank  $> 2$  in our terminology), then, in fact,  $\Gamma$  satisfies the linear inequality with  $I(t) = t$  (which makes the 2-dimensional isoperimetric rank infinite). The groups (and spaces) with this property are called *hyperbolic* and have been extensively studied in recent years.

(c) It is unclear how to approach the  $q$ -dimensional isoperimetric problem for  $q \geq 3$  without the above condition  $\pi_i = 0$  for  $i \leq q-1$  (which was actually missing in the French edition of the book). Also, one should be more specific here on the allowed topology of manifolds (or rather pseudo-manifolds)  $S$  involved in the definition. For example, one can stick to  $(n-1)$ -spheres which are allowed to be filled in (spanned) by  $q$ -balls. Or, we can look at  $(q-1)$  tori filled by solid  $q$  tori, as suggested by the cartesian products  $\Gamma_1 \times \Gamma_2 \times \dots \times \Gamma_{q-1}$  (see [Al–Pr–Wa]).

These  $q$ -dimensional isoperimetric inequalities can yield nonexistence

results for mappings in the spirit of the following

**6.35. Theorem:** *Let  $W$  be a compact Kähler manifold such that  $\pi_2(W) = 0$  and such that  $\pi_1(W)$  is hyperbolic (i.e.,  $\pi_1(W)$  has 2-dimensional isoperimetric rank strictly greater than 2). Then there is no nonconstant holomorphic map of  $\mathbb{C}$  into  $\tilde{W}$ .*

**Proof.** Let  $\omega$  denote the Kähler form of  $W$ . For a compact subset  $A \subset \mathbb{C}$  and a  $C^1$  mapping  $f : A \rightarrow W$ , the integral  $\int_A \|f_*\xi\|$ , where  $\xi$  is the constant 2-vector field  $\frac{\partial}{\partial z} \wedge \frac{\partial}{\partial z}$  on  $\mathbb{C}$ , is, by definition, the area of  $f(A)$ . In this notation, we have

$$\int_A f^* \omega = \int_A \langle \omega, f_* \xi_{f(x)} \rangle dx.$$

By Wirtinger's inequality, however,

$$\langle \omega, f_* \xi_{f(x)} \rangle \leq \frac{1}{2} \|f_* \xi\|$$

(see [Fed]GMT, p. 40) with equality if and only if the simple 2-vector  $f_*\xi$  can be written as  $v \wedge iv$  for some tangent vector  $v$ . It follows that  $\text{Area}(f(A)) \geq 2 \int_A f^* \omega$ . Since  $\pi_2(W) = 0$ , all extensions of a curve  $\partial A \rightarrow W$  are homotopic, and so the integral  $\int_A f^* \omega$  depends only on  $A$ . Thus, if  $f_0$  is such an extension, then the area of  $f$  is necessarily no less than  $|\int_A f^* \omega| = |\int_A f_0^* \omega|$ , and this value is attained precisely by the holomorphic extensions. Given a nonconstant holomorphic map  $f : \mathbb{C} \rightarrow W$ , we denote by  $p$  the function  $\|Df\|$ . By Ahlfors' Lemma (Lemma 6.9),  $(\mathbb{C}, pg_{eucl})$  has isoperimetric dimension less than 2; for each  $m > 2$ , there is a sequence  $A_i$  of compact sets in  $\mathbb{C}$  such that

$$\text{vol}_{pg}(A_i) \rightarrow \infty \quad \text{and} \quad \frac{\text{vol}_{pg}(A_i)}{(\text{vol}_{pg}(\partial A_i))^{-m/(m-1)}} \rightarrow \infty$$

as  $i \rightarrow \infty$ . Since  $f$  is holomorphic,

$$\text{vol}(f(A_i)) = \text{vol}_{pg}(A_i) \quad \text{and} \quad \text{vol}(f(\partial A_i)) = \text{vol}_{pg}(\partial A_i)$$

and  $f$  is the extension of  $f|_{\partial A_i}$  to  $A_i$  having minimal area. We conclude that  $W$  has 2-dimensional isoperimetric dimension less than  $m$ .

The preceding theorem suggests a way to define quasiregular mappings from one manifold into another manifold of larger dimension: The minimal property for holomorphic mappings between Kähler manifolds should be replaced by a “quasiminimal” property.

**6.36. Definition:** Let  $V_0$  be a compact manifold with boundary. A mapping  $f: V_0 \rightarrow W$  is called *C-quasiminimal* if, for each map  $g: V_0 \rightarrow W$  such that  $f|_{\partial V_0} = g|_{\partial V_0}$  and such that the chains  $f(V_0), g(V_0)$  are homologous in  $W$  modulo the boundary  $f(\partial V_0) = g(\partial V_0)$ , we have  $\text{vol}(f(V_0)) \leq C \text{vol}(g(V_0))$ .

If  $V$  is an arbitrary manifold, then a mapping  $f: V \rightarrow W$  is called *quasiminimal* if there is a constant  $C$  such that the restriction of  $f$  to each compact submanifold of  $V$  with boundary is  $C$ -quasiminimal.

**6.37. Example:** If  $f: V \rightarrow W$  is quasiregular (with  $\dim(V) = \dim(W)$ ), then the graph  $Gf: V \rightarrow V \times W$  given by  $G(x) = (x, f(x))$  is quasiminimal.

To see this, let  $pr_1, pr_2$  be the projections onto the factors of the product  $V \times W$ , and let  $\omega_1, \omega_2$  be the volume forms on  $V, W$ . Then  $\omega = pr_1^*\omega_1 + pr_2^*\omega_2$  is a closed form on  $V \times W$  satisfying the inequality

$$\begin{aligned} |\langle \omega, X_1 \wedge \cdots \wedge X_n \rangle| &\leq \|pr_{1*}(X_1 \wedge \cdots \wedge X_n)\| + \|pr_{2*}(X_1 \wedge \cdots \wedge X_n)\| \\ &\leq 2\|X_1 \wedge \cdots \wedge X_n\|, \end{aligned}$$

for each simple  $n$ -vector  $X_1 \wedge \cdots \wedge X_n$  of  $V \times W$ .

In particular, if  $g: V_0 \rightarrow V \times W$  and if  $\xi$  denotes the  $n$ -vector of  $V$  dual to  $\omega_1$ , in the sense that  $\langle \omega_1, \xi \rangle = 1$ , then

$$\begin{aligned} \text{vol}(g(V_0)) &= \int_{V_0} \|g_*\xi(x)\| dx \\ &\geq \frac{1}{2} \int_{V_0} |\langle \omega, g_*\xi(x) \rangle| dx \\ &\geq \frac{1}{2} \left| \int_{V_0} g^*\omega \right| \\ &= \frac{1}{2} \left| \int_{g(V_0)} \omega \right| \\ &= \frac{1}{2} \left| \int_{Gf(V_0)} \omega \right|, \end{aligned}$$

when the chains  $g(V_0)$  and  $Gf(V_0)$  are homologous, since  $\omega$  is closed. This integral equals  $(1/2) \int_{V_0} (1 + J(f, x)) dx$ . We now write  $\xi = v_1 \wedge \cdots \wedge v_n$ . Then

$$\|Gf_*\xi\| = \|(v_1 + Df_{v_1}) \wedge \cdots \wedge (v_n + Df_{v_n})\|$$

is less than or equal to a polynomial of degree  $n$  in  $\|Df\|$ , and so there are constants  $A, B$  such that  $\|Gf_*\xi\| \leq A + B\|Df\|^n$  so that  $\text{vol}(Gf(V_0)) \leq$

$A \text{vol}(V_0) + B \int_{V_0} \|Df_x\|^n dx$ . If  $f$  is  $C$ -quasiregular, then

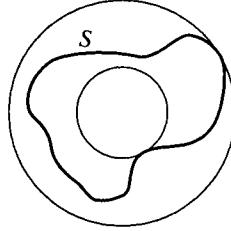
$$\text{vol}(Gf(V_0)) \leq C' \left( \frac{1}{2} \text{vol}(V_0) + \frac{1}{2} \int_{V_0} J(f, x) dx \right) \leq C' \text{vol}(g(V_0)),$$

for  $C' = \sup(2A, 2CB)$ , and so  $Gf$  is quasiminimal.

**6.37+** It is unclear what a suitable notion of “quasiconformality” should be for maps  $V \rightarrow W$ , where  $\dim W < \dim V$ . One general possibility is to require the image of every small ball  $B_V \subset V$  to be a *quasi-ball* in  $W$ , i.e., pinched between two concentric balls in  $W$ ,

$$B_w(\rho) \subset f(B_v) \subset B_w(C\rho),$$

where  $w = f(v)$  and  $C = C(f) > 0$  is some constant.



For example, if  $f: V \rightarrow W$  is a smooth *submersion*, then this is equivalent to a bound on the norm of the differential by the Jacobian of  $f$  on the subbundle  $S \subset T(V)$  normal to the kernel  $\ker Df \subset T(V)$  at each point of  $V$ ,

$$\|D^* D\|_v^n \leq \text{const} \det(D^* D|_{S_v}),$$

$v \in V$ . But to get off the ground, one should work out basic examples, e.g., to show that *no* such map  $f: \mathbb{R}^{n+1} \rightarrow \mathbb{R}^n$  has a *bounded* image for  $n \geq 2$  (or maybe 3). (Since this is unknown, one may strengthen the assumptions above by trying to rule out some particular maps  $f: \mathbb{R}^{n+1} \rightarrow B^n \subset \mathbb{R}^n$ , such as smooth fibrations where, moreover, the norm of the differential does not change much along each fiber  $f^{-1}(x) \subset \mathbb{R}^{n+1}$ .)

Another possibility is to fix some  $n$ -dimensional subbundle  $S \subset T(V)$  *beforehand* and to study maps  $f: V \rightarrow W = W^n$  which are *quasiconformal in  $S$* . Here one may look at the contact subbundle  $S$  on the  $(2n+1)$ -dimensional Heisenberg group  $H_{2n+1}$  and again try to rule out *bounded* maps  $H_{2n+1} \rightarrow \mathbb{R}^{2n}$ .

**Remark +:** It seems difficult (if at all possible) to make up a meaningful local metric definition of quasiconformality for maps  $V \rightarrow W$ , where

$\dim V < \dim W$ . On the other hand, the above “quasi-ball definition” extends to arbitrary metric spaces, where it turns out to be quite productive, as for example in the case of Carnot–Caratheodory spaces.

**6.38. Example:** Let  $\Omega$  be a pseudoconvex open subset of  $\mathbb{C}^2$ . In each tangent space  $T_x\partial\Omega$ , the set of vectors preserved under multiplication by  $i = \sqrt{-1}$  is a 2-plane. Thus, we obtain a generally nonintegrable field of 2-planes on  $\partial\Omega$  with which we can associate a “Carnot” metric (see 1.18 and 3.17).

*If  $\Omega$  is the ball  $B^4$ , then this metric on  $S^3 = B^4$  is conformally equivalent to the metric introduced in 3.17 on the Heisenberg group.*

Indeed, let  $B^4$  be equipped with its Bergman metric (see [Weil]), so that  $B^4$  is isometric to the complex hyperbolic plane,

$$\mathbb{H}_{\mathbb{C}}^2 = (U(1) \times U(2)) \backslash U(1, 2).$$

More precisely,  $U(1, 2)$  is the group of matrices or endomorphisms of  $\mathbb{C}^3$  that preserve the Hermitian form

$$q(x) = -|x_1|^2 + |x_2|^2 + |x_3|^2,$$

and so  $U(1, 2)$  operates on the set

$$H = \{x \in \mathbb{C}^3 : q(x) = -1\},$$

and thus on the projection

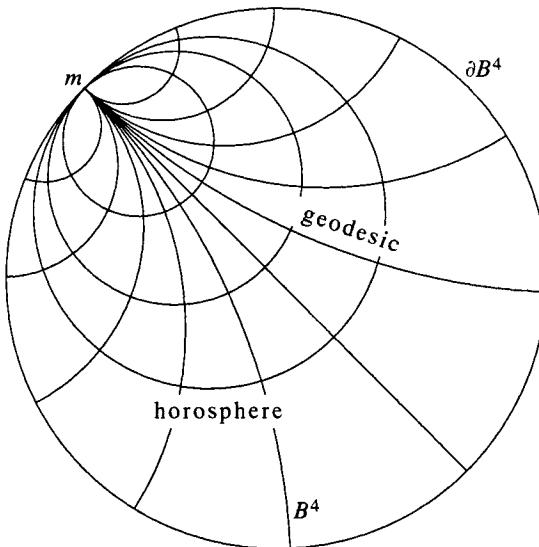
$$p(H) = B^4 \subset \mathbb{C}^2 \subset \mathbb{CP}^2.$$

The action of  $U(1, 2)$  also preserves  $\partial B^4 = p(\{q = 0\})$  and the field of 2-planes on  $\partial B^4$  defined above. We now show that the stabilizer of a point of  $\partial B^4$  contains a subgroup isomorphic to the Heisenberg group. Let  $J$  be the matrix of the quadratic form  $q$ , i.e.,

$$J = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

The Lie algebra  $\mathfrak{u}(1, 2)$  of  $U(1, 2)$  is the set of  $3 \times 3$  matrices  $M$  such that  $M^*J + JM = 0$ . Such a matrix can be written as

$$M = \begin{pmatrix} ir & a & b \\ a & is & -c \\ b & c & it \end{pmatrix},$$



where  $a, b, c \in \mathbb{C}$  and  $r, s, t \in \mathbb{R}$ . Choose a point  $m$  in the sphere, for example  $m = p(v)$ , where  $v = (1, 1, 0) \in \mathbb{C}^3$ . The stabilizer  $F$  of  $m$  is the subgroup  $\{g \in U(1, 2) : gv \text{ is colinear to } v\}$ ; thus its Lie algebra is

$$\begin{aligned}\mathfrak{f} &= \{M \in \mathfrak{u}(1, 2) : Mv \text{ is colinear to } v\} \\ &= \{M \in \mathfrak{u}(1, 2) : b = -c, r = s, a \in i\mathbb{R}\}.\end{aligned}$$

Set

$$X = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 1 & -1 & 0 \end{pmatrix}, Y = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & -i \\ i & -i & 0 \end{pmatrix}, Z = \begin{pmatrix} i & -i & 0 \\ i & -i & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

so that  $[X, Z] = [Y, Z] = 0$  and  $[X, Y] = Z$ , so that the real vector space generated by  $X, Y, Z$  is a Lie subalgebra  $\mathfrak{n}$  of  $\mathfrak{f}$  isomorphic to the Lie algebra of the Heisenberg group. From this we can deduce that the homomorphism  $\varphi$  from the Heisenberg group  $N$  into  $U(1, 2)$  whose differential at the origin sends the plane orthogonal to the center onto the plane spanned by  $X, Y$ , which is a complex line in  $\mathfrak{u}(1, 2)$ . The mapping  $j : N \rightarrow \partial B^4$  given by  $j(n) = \varphi(n)(m')$  for a point  $m' \in \partial B^4$ .

It remains to show that  $j$  is a homeomorphism onto  $\partial B^4 \setminus \{m\}$ , which is simple, and that it is conformal, which follows from the formula  $\|j_*(\alpha X + \beta Y)\|^2 = 3(\alpha^2 + \beta^2)$  at the origin and from the fact that  $N$  acts by homographies, which are conformal transformations of  $\mathbb{CP}^n$ .

**6.39. Remark:** Since all contact structures in dimension 3 are locally iso-

morphic, it follows that for any pseudoconvex domain  $\Omega \subset \mathbb{C}^2$ , the Carnot–Caratheodory metric on  $\partial\Omega$  is locally quasi-isometric to that of  $S^3$ .

**6.40. Question:** Under what conditions on  $\Omega$  does there exist a locally quasiconformal homeomorphism from the Heisenberg group into  $\partial\Omega$  when both are equipped with their Carnot–Caratheodory metrics?

**6.41<sub>+</sub> Remark.** A full-fledged quasiconformal theory for C-C geometry is developed in [Kor–Rei], see also [Gro]<sub>CC</sub>.

**6.42<sub>+</sub> The Bloch–Brody principle for quasiconformal maps.** This principle, discovered I believe by A. Bloch a long time ago and revived by Brody in recent times, allows one to obtain, by some limiting process, a *uniformly continuous* map  $\mathbb{R}^n \rightarrow W$  quasiconformal in some sense, starting from a nonuniformly continuous, quasiconformal map or a suitable sequence of maps  $V_i \rightarrow W$ . To see how it works, imagine for the moment that the maps in question are  $C^1$ -smooth (e.g. holomorphic from  $\mathbb{R}^2 = \mathbb{C}$  to a compact complex manifold as in the original papers by Bloch and Brody) and try to make a given  $f : \mathbb{R}^n \rightarrow W$  Lipschitz by moving the origin to the point  $v_0$  where the norm of the differential  $\|Df\|_v$  assumes its maximum. Of course, this does not work if the function  $\|Df\|_v$  is unbounded on  $\mathbb{R}^n$ , but we can artificially make it bounded by restricting  $f$  to a large ball  $B(R)$  in  $\mathbb{R}^n$  about the origin and taking the complete hyperbolic metric  $g_R$  with curvature  $-1$  on this  $B(R)$ . Since  $g_R$  blows up at the boundary of  $B(R)$ , the norm of the differential  $Df$  on  $B(R)$  with respect to  $g_R$  does assume its maximum at some point, say  $v_R \in B(R)$ , and by rescaling  $(B(R), g_R)$  with  $\lambda = \|Df(v_R)\|_{g_R}$ , we shall make  $\|Df(v_R)\| = 1$  for the metric  $\lambda g_R$ . Then we take a sequence  $R_i \rightarrow \infty$  and go to the pointed Lipschitz limit

$$\lambda_i(B(R_i), g_{R_i}) \xrightarrow{\text{Lip}} \mathbb{R}^n$$

for  $i \rightarrow \infty$  with 1-Lipschitz maps  $f_i = f|_{B(R_i)}$  hopefully converging, perhaps after passing to a subsequence, to some (*nonconstant!*) map  $f_\infty : \mathbb{R}^n \rightarrow W$  where  $\|Df_\infty\|$  assumes its maximum at the origin. Now, in the situations we deal with, the nonconstancy of  $f_\infty$  is automatic. The only problem which needs attention is the possibility that  $f_i(v_{R_i}) \rightarrow \infty$  in  $W$ . This, however, does not present itself if  $W$  is compact or, more generally, when  $W/\text{Isom}(W)$  is compact, since  $f_i(v_{R_i})$  can be moved to a compact region of  $W$ . Furthermore, if  $W/\text{Isom}(W)$  is noncompact, but, for example,  $W$  is complete with *bounded local geometry*, then we also can go to the Lipschitz limit of (a subsequence of) the sequence  $(W, w_i)$ ,  $w_i = f_i(v_{R_i})$  as  $i \rightarrow \infty$  and come up with  $f : \mathbb{R}^n \rightarrow W_\infty$ . And even if  $W$  has unbounded geometry but still satisfies some asymptotic finiteness property,

say  $\sup_{w \in W} K_w(W) < \infty$ , we can pass to the pointed Hausdorff limit of  $(W, w_i)$  with some “virtual quasiconformal map”  $f_\infty$  from  $\mathbb{R}^n$  to some “virtual  $n$ -manifold” fibered over  $W_\infty$  of (possibly)  $\dim W_\infty < n$ .

This works, as it stands for holomorphic maps from  $\mathbb{C}$ , and more generally for *pseudoholomorphic* maps to quasicomplex manifolds. Here we are interested in quasiconformal maps where the above leads to the following conclusion.

**6.42<sub>2+</sub>** **Proposition.** *Let  $W$  be a complete Riemannian manifold such that  $W/\text{Isom}(W)$  is compact. If there exists a nonconstant quasi-regular (quasiconformal) map  $f : \mathbb{R}^n \rightarrow W$ , then there also exists a uniformly continuous quasiregular (respectively, quasiconformal) map  $f_\infty : \mathbb{R}^n \rightarrow W$  which is necessarily uniformly Hölder for some exponent  $\alpha$ .*

**Remarks:** This has several generalizations. For example, instead of having a single map  $f$ , we can start with a sequence  $f_i : V_i \rightarrow W$  where all the  $V_i$  are complete manifolds with  $|K(V_i)| \leq \text{const} < \infty$ . Then, assuming that these  $f_i$  are not together (as a family) uniformly continuous (i.e., equicontinuous), we can produce  $f_\infty : \mathbb{R}^n \rightarrow W$  as above. Furthermore, we can apply the same to quasiminimal quasiconformal non-equidimensional maps  $\mathbb{R}^n \rightarrow W^{n+k}$ . Finally, this can be used in the Carnot-Caratheodory framework, since we do not truly need hyperbolic metrics in domains (e.g., balls)  $U \subset V$ . Actually, a good enough metric  $g_U$  is obtained by blowing up  $g_V|_U$  by the conformal factor  $\delta(U) = \text{dist}(u, \partial U)$  (or  $\delta^\alpha(u)$  with any  $\alpha > 0$  for this matter). All one needs to check is (local) precompactness of these metrics as well as the scaled  $\lambda(U, \delta g_V)$  for  $\lambda \geq 1$ , in the pointed Lipschitz topology. (We suggest that the reader think through all of this by him/herself.)

**6.42<sub>3+</sub>** **Problems.** (a) Are closed manifolds  $W = W^n$  receiving quasiregular maps  $\mathbb{R}^n \rightarrow W$  elliptic in the sense of Ch. 2.E<sub>+</sub>? Is the converse true?

(b) Can we derive the Rickman-Picard theorem (see [Rickm]) for quasiregular maps  $f$  by a purely isoperimetric argument? Notice that the Hölder property of  $f$  does follow in this way (see §2.6 in [Gro]CC) and thus extends to quasiconformal quasiminimal maps  $f : \mathbb{R}^n \rightarrow W^{n+k}$ , but it is unknown if Rickman’s theorem does as well.

(c) Let  $V$  and  $W$  be equidimensional Riemannian homogeneous spaces. When does there exist a quasiconformal (quasiregular) map  $f : V \rightarrow W$ ? Does the existence of this make the isoperimetric dimension of  $V$  greater than that of  $W$ ? The same question arises for  $V$  with compact  $V/\text{Isom } V$  and an arbitrary  $W$ .

## E<sub>+</sub> The Varopoulos isoperimetric inequality

**6.43.** There is the following quite popular general strategy for bounding the volume of  $\partial D$ . Suppose we have means of transportation of mass from  $D$  to the complement  $V \setminus D$ . In the course of this, we necessarily cross  $\partial D$ , and we can sometimes estimate the amount of mass passing through  $\partial D$  by  $\text{vol } \partial D$ . Thus, we can bound  $\text{vol } D$  provided that we have a lower bound on the percentage of the total mass (volume) of  $D$  that is being transported.

**Examples:** (a) Suppose our “transportation” is given by a vector field  $X$  on  $D$ . This is seen as an “infinitesimal transport,” where the mass crossing the boundary per unit time is obviously bounded by  $\int_{\partial D} \|X\|$ . On the other hand, the infinitesimal percentage of the transported mass equals  $\int_D \text{div } X$ , and by Stokes’ formula,

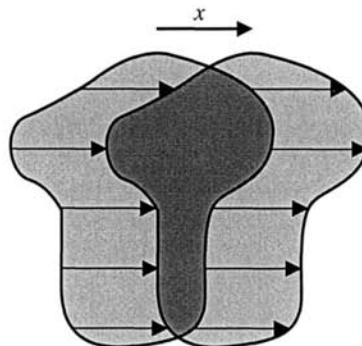
$$\int_D \text{div } X \leq \int_{\partial D} \|X\| \leq \sup \|X\| \text{ vol}(\partial D).$$

This gives a bound on  $\text{vol } D$  if  $\text{div } X \geq \varepsilon > 0$ , and  $\|X(v)\| \leq C$ , that is,

$$\text{vol } D \leq \varepsilon^{-1} C \text{ vol}(\partial D)$$

(we already saw how this applies to domains in hyperbolic space, for example).

- (b) Take some  $D \subset \mathbb{R}^n$  and translate it by a vector  $x \in \mathbb{R}^n$ .



The amount of mass transported through  $\partial D$  in this way is obviously bounded by  $\|x\| \text{ vol } \partial D$ , and to bound  $\text{vol } D$  by  $\text{vol } \partial D$ , we need a vector  $x$  which moves much of  $D$  outside of  $D$ . To find such an  $x$ , we consider all  $x$  with  $\|x\| \leq d$  and observe that the average transport of mass can be computed as follows. Let  $\varphi$  denote the characteristic (indicator) function

of  $D$ , and let  $\varphi_d$  be the smoothing of  $\varphi$  by means of the *smoothing kernel*

$$S(x, y) = \begin{cases} \alpha_d^{-1} & \text{for } \text{dist}(x, y) \leq d \\ 0 & \text{for } \text{dist}(x, y) \geq d, \end{cases}$$

where  $\alpha_1 d^n$  denotes the volume of the  $d$ -ball  $B(d)$  in  $\mathbb{R}^n$ . Then the above transport, say  $T_x$ , averaged over  $x \in B(d)$  (obviously) equals

$$\int_D |\varphi(y) - \varphi_d(y)| dy, \quad (*)$$

where

$$\varphi_d(y) = \alpha_d^{-1} \text{vol}(B_y(d) \cap D)$$

for  $y \in \mathbb{R}^n$ . Now let us choose  $d$  such that  $\alpha_d = \text{vol } B(d) = 2 \text{vol}(D)$ . Clearly,  $\varphi_d(y) \leq 1/2$  for all  $y \in D$ , and so at least half of the mass of  $D$  is transported away from  $D$  by  $x$  with  $\|x\| \leq d$ . It follows that some  $x$  with  $\|x\| \leq d$  gives us the inequality

$$d \text{vol } \partial V \geq \frac{1}{2} \text{vol } D,$$

where

$$2 \text{vol } D = \alpha_d = \nu_n d^n$$

for  $\nu_n = \text{vol}(B(1))$ . Thus,

$$(2\nu_n^{-1} \text{vol } D)^{1/n} \text{vol}(\partial V) \geq \frac{1}{2} \text{vol}(D),$$

or

$$\text{vol } D \leq \gamma_n (\text{vol } \partial D)^{n/(n-1)} \quad (+)$$

for  $\gamma_n = (2(2\nu_n^{-1}))^{1/(n-1)}$ , which is a rather neat proof (due to Minkowski, I guess) of the isoperimetric inequality in  $\mathbb{R}^n$ , albeit with a nonsharp constant.

**Exercise:** Improve the above constant by a better evaluation of the mass crossing through  $\partial D$  averaged over  $x \in B(d)$  with the angle between  $x$  and  $\partial D$  taken into account.

Now we come to the subject matter of this section, i.e., to a finite subset  $D$  in a group  $\Gamma$  equipped with the word metric associated to a finite generating subset in  $\Gamma$ . We transport  $D$  by using *left* translates by  $\gamma \in \Gamma$ , where we recall that our metric  $\|\alpha\beta^{-1}\|$  in  $\Gamma$  is *right* invariant. Every left translate  $\delta \mapsto \gamma\delta$ ,  $\delta \in D$ , moves  $\delta$  by the distance  $\|\gamma\|$ , since

$$\text{dist}_\Gamma(\delta, \gamma\delta) = \|\delta(\gamma\delta)^{-1}\| = \|\gamma\|,$$

and the amount of mass transported away from  $D$  does not exceed  $\|\gamma\| \operatorname{card}(\partial D)$ . Indeed,  $\gamma$  can be decomposed into  $\|\gamma\|$  “elementary moves” corresponding to the generators of  $\Gamma$ , where each elementary transport lands in the boundary of  $D$ , since these move the points by distance one (where we recall that  $\partial D = \{\alpha \in \Gamma : \operatorname{dist}(\alpha, D) = 1\}$ ). Then we average these  $\gamma$ -transportations over all  $\gamma \in B(d) \subset \Gamma$  for the minimal  $d$ -ball  $B(d)$  having  $\operatorname{card} B(d) \geq 2 \operatorname{card} D$ , as in (b) above. This immediately leads to the inequality

$$d \operatorname{card}(\partial D) \geq \frac{1}{2} \operatorname{card} D, \quad (\star)$$

where  $\operatorname{card} B(d) \approx 2 \operatorname{card} D$ . For example, if the group  $\Gamma$  is nilpotent and the balls have polynomial growth of degree  $n$ ,

$$\operatorname{card} B(d) \simeq d^n,$$

then our  $d$  in  $(\star)$  is  $\simeq (\operatorname{card} D)^{1/n}$ , which gives the expected inequality

$$\operatorname{card} D \leq \operatorname{const} (\operatorname{card} \partial D)^{n/(n-1)} \quad (\star)_n$$

proven earlier by Pansu for the Heisenberg group (see [Pan]IIGH).

Furthermore, if  $\Gamma$  is not virtually nilpotent, and hence the balls grow faster than polynomially (see [Dri–Wil]), then  $(\star)_n$  holds for *all*  $n$ , which means that  $\Gamma$  has infinite isoperimetric dimension. And, if  $\Gamma$  has exponential growth (e.g. being solvable but not virtually nilpotent), then we take  $d \simeq \log(\operatorname{card}(D))$  and get the isoperimetric bound

$$\operatorname{card}(\partial D) \geq \operatorname{const} \operatorname{card}(D) / \log(\operatorname{card}(D)).$$

**Remarks.** (a) All these isoperimetric inequalities in  $\Gamma$  are due to Varopoulos, who originally used a more complicated transportation associated to the random walk in  $\Gamma$  (see [Va–Sa–Co] and [Pit–Sal], where stronger results can be found). The simple proof above appears in [Coul–Sal] and in [Coul]. Another simple transportation argument can be found in [Gro]cc.

(b) One can transport the measure away from  $D$  following the geodesic flow in the unit tangent bundle  $U(V) \rightarrow V$ , where  $D$  is first lifted to  $U(V)$ , then transported according to  $\operatorname{geo}_t$  for some  $t \in [0, d]$  and finally projected back to  $V$ . This idea goes back to Santalo and leads to interesting corollaries whenever we can show that a sufficient amount of mass goes away from  $D$  for a given  $d$ . For example, if  $V$  is complete, simply connected, and without conjugate points, then every geodesic of length  $\geq \operatorname{diam} D$  starting in  $D$  leaves  $D$ . It follows easily that

$$\operatorname{vol} D \leq \operatorname{const}_n (\operatorname{diam} D) (\operatorname{vol} \partial D).$$

Then, if we want to exclude  $\text{diam } D$ , we need *a priori* an extra lower bound on the amount of mass transported by  $\text{geo}_t$ , which can be achieved, for example, with the Jacobian of the exponential map  $E : T_v(V) \rightarrow V$ . For example, if

$$\|\text{Jacobian } E_v(x)\| \geq C_0,$$

then

$$\text{vol } D \leq \text{const}(n, C_0)(\text{vol } \partial D)^{n/(n-1)}$$

as the logic of our argument shows (see [Gro] for better results).

(c) There is nothing sacred about the geodesic flow in this argument. One could take an arbitrary measure space  $U$  fibered over  $V$  and try some measure-preserving flow in  $U$ . This works very nicely, for example, for the time-shift flow in the space of (Brownian) paths in  $V$  with the Wiener measure (as was observed by J. Moser years ago) and relate this isoperimetric inequality to the rate of decay of the heat flow in  $V$ .

**Problem:** Is there a *necessary and sufficient* condition for a given isoperimetric inequality in  $V$  in terms of the existence (or nonexistence) of the above flow or just some (kernel) functions  $S_d(x, y)$  in  $V$ ? (We do know in this regard that being open at infinity, i.e., satisfying  $\text{vol } D \leq C \text{ vol } \partial D$  is equivalent to the existence of a  $(n - 1)$ -form  $\eta$  with  $\|\eta\|_v \leq C$  such that  $d\eta$  is a volume form. This follows by an application of the Hahn-Banach theorem (as in the Whitney mass-comass duality of our section 4.D), which was indicated to me by D. Sullivan about twenty years ago.)

# Chapter 7

## Morse Theory and Minimal Models

### A. Application of Morse theory to loop spaces

**7.1.** In Chapter 6, we introduced the notion of 2-dimensional isoperimetric rank (6.32) as the largest number  $p$ , such that each simple curve of length  $\ell$  is bounded by a disk of area at most  $C\ell^{p/p-1}$ . This definition only makes sense in noncompact manifolds, and we have shown that the 2-dimensional isoperimetric rank of the universal cover of a compact manifold  $V$  depends only on the fundamental group  $\pi_1(V)$ .

We can also ask if it is possible to deform a given loop  $\ell$  to a point without increasing its length, or without increasing its length beyond  $f(\ell)$ , where the function  $f$  would arise as an invariant of the geometry of the (universal cover of the ) manifold. The answer to this question may vary depending on  $V$ : For the universal cover of a manifold of nonpositive curvature, we can take  $f(\ell) = \ell$ . These manifolds, although cocompacts of very different groups, are the simplest possible from the point of view of the invariant  $f$ . On the other hand, we will see that, when a universal cover or fundamental group is so complicated that the word problem cannot be solved, then the function  $f$  is not computable. Between these two extremes, it is unclear whether we can say much about the invariant  $f$  in the non-compact case. Nevertheless, the invariant  $f$  makes sense for a compact manifold  $V$ , as illustrated in Figure 2.26, for which we already have several results: Scolie 2.27 shows that  $f(\ell) \leq C(V)\ell$ , while Proposition 2.26 gives

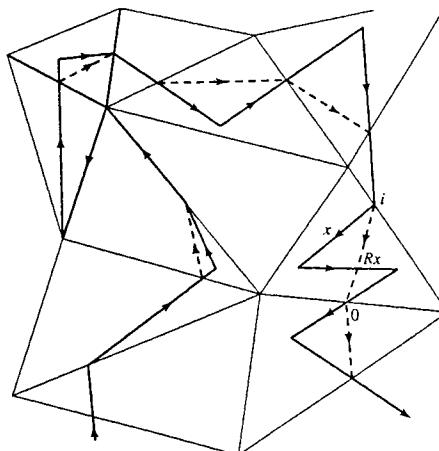
$f(\ell)/\ell \rightarrow 1$  as  $\ell \rightarrow \infty$ .

It is interesting to compare the topology of all the spaces  $X_\ell$  of loops of length  $\leq \ell$  and not just that of their connected components.

**7.2.** We now introduce some notation. Let  $X$  (resp.  $Y$ ) be the space of piecewise  $C^\infty$  paths connecting  $w$  to  $w'$  in a compact Riemannian manifold  $W$  (resp. the space of closed, piecewise  $C^\infty$  curves without base point in  $W$ ), both equipped with the  $C^\infty$  topology, so that the length function  $L$  is continuous. We denote by  $X_t = L^{-1}([0, t])$  (resp.  $Y_t$ ) the space of paths (resp. curves) of length at most  $t$ . Finally, we let  $dm(t)$  be the largest integer  $d$  such that for each  $i$  with  $0 \leq i \leq d$ , the homomorphism in homology induced by inclusion  $X_t \hookrightarrow X$  (resp.  $Y_t \hookrightarrow Y$ ) is surjective.

**7.3. Theorem:** *If  $W$  is a compact, simply connected Riemannian manifold with path space  $X$  and space  $Y$  of unbased loops, there are constants  $c, C$  such that  $ct \leq dm(t) \leq Ct$ .*

**Proof.** Fix a triangulation  $Tr$  of  $W$  and let  $X'$  denote the space of piecewise linear paths for this triangulation, where we assume that the endpoints  $w$  and  $w'$  are vertices (and where the case  $Y$  of closed curves is left to the reader so that we do not have to carry along the omnipresent “resp.”). Every path in  $X'$  is given by a sequence of points  $w = w_1, w_2, \dots, w_k = w'$  in  $W$ , where every two neighboring points  $w_i$  and  $w_{i+1}$  lie in one simplex  $\Delta$  of  $Tr$  and are joined in  $\Delta$  by the (unique) straight segment.



Thus,

$$X' = \bigcup_{k=1}^{\infty} X'_k,$$

where  $X'_k$  denotes the space of paths with at most  $k$  vertices. Also observe that for every sequence of simplices  $\Delta_1, \dots, \Delta_k$  in  $Tr$ , the paths with the vertices  $w_i \in \Delta_i$  make a cell in  $X'_k$ , namely  $\Delta_1 \times \Delta_2 \times \dots \times \Delta_k$ . Thus,  $X'$  comes along with a natural cell decomposition  $Tr'$  with  $X'_k$  being contained in the  $k_n$ -skeleton  $Tr_{kn}$  of  $Tr'$ .

**7.3 $\frac{1}{2}_+$  Lemma.** *Every continuous map  $f$  of a  $d$ -dimensional polyhedron  $P$  into a compact  $X$  can be homotoped to a map whose image lies in the  $d$ -skeleton  $Tr'_d \subset X' \subset X$ .*

**Proof.** Maps  $f: P \rightarrow X$  correspond to maps  $F: P \times [0, 1] \rightarrow W$ , and these admit simplicial approximations  $F': P \times [0, 1] \rightarrow W$  for sufficiently fine triangulations of  $P \times [0, 1]$ . But, every simplicial map  $F'$  of  $P \times [0, 1]$  to  $W$  gives us a map from  $P$  to  $X'$  which lands in some  $d'$ -skeleton  $Tr'_{d'}$  from where it can be homotoped to  $Tr'_d$ .

All this is quite trivial and has nothing to do with the simple connectedness of  $W$ . But, for the following lemma, this is crucial

**7.3 $\frac{2}{3}_+$  Lemma.** *If  $w = w'$ , then there is a homotopy of  $Tr'_d$  in  $X$  moving it to  $X_t \subset X$  with  $t \leq \text{const } d$  for  $\text{const} = \text{const}(W, Tr)$  independent of  $d$ .*

**Proof.** Let  $\alpha: W \rightarrow W$  be a smooth map homotopic to the identity and sending the 1-skeleton of the triangulation  $Tr$  of  $W$  to the point  $w \in W$ . This induces a map, say  $\alpha': X \rightarrow X$ , also homotopic to the identity. Let us see what this  $\alpha'$  does to a  $d$ -cell in  $Tr'$ . Such a cell is the product  $\Delta_1 \times \Delta_2 \times \dots \times \Delta_k$ , where  $\sum_{i=1}^k \dim \Delta_i = d$ . It follows that the number of these simplices of dimension  $> 1$  does not exceed  $d$ , and those which have dimension zero correspond to pairs of vertices, i.e., edges in  $Tr$ . These are contracted to a single point in  $W$ , and so the path corresponding to any point in  $Tr'_d$  is transformed to a new path consisting of at most  $d$  pieces, each of the form  $\alpha(I_i)$ , where  $I_i$  is a straight segment in some simplex  $\Delta_i \subset W$ . Thus, the length of this path does not exceed  $\text{const } d$ .

This proves the inequality  $ct \leq dm(t)$  for  $c$  equal to the  $\text{const} = \text{const}(W, Tr)$  above (which depends on  $\alpha$  in practice), since every  $i$ -cycle for  $i \leq d$  is moved to  $X_{cd}$ , provided that  $w = w'$ , and then the case  $w \neq w'$  follows trivially.

Finally, in order to prove the opposite inequality, we observe that the paths in  $X_t$  can be replaced by piecewise geodesic paths with  $d \leq C_0 t$  segments, which makes this space homotopy equivalent to a simplicial complex of dimension  $d' \leq Ct$  (compare [Milnor]MT, where again we do not need  $\pi_1(W) = 0$ ). And then, we just refer to the nonvanishing of  $H_i(X)$  for a set of  $i \in \mathbb{N}$  containing an arithmetic progression (see [Klin], [Sul]ICT). This

trivially implies that  $dm(t) \leq Ct$ .

**Remarks<sub>+</sub>.** (a) If a manifold  $W$  has positive Ricci curvature, then the index of a geodesic is roughly proportional to its length, which leads to the conclusion  $dm(t) \geq ct$ . This could have been useful as a necessary criterion for the existence of a metric on  $W$  with  $\text{Ricci} > 0$  if not for Theorem 7.4. Now, in view of 7.4, one might think that there are hardly any stable homotopy restrictions preventing  $W$  from having a metric with  $\text{Ricci} > 0$ . For example, one may expect that, for every finite (or, more generally, locally finite), simply connected, finite dimensional polyhedron  $P$ , there exists a complete  $W$  homotopy equivalent to  $P$  (or at least to a suspension of  $P$ ) with  $\text{Ricci } W > 0$ . And even if one looks at *closed* simply connected manifolds  $W$ , it seems that most of them are homotopy equivalent to those with  $\text{Ricci} > 0$ , at least after a suitable stabilization, such as passing to  $W \times S^2$ , or by taking a connected sum of two copies of  $W$  with opposite orientations, etc. In fact, all known ( $C^\infty$  as well homotopy) obstructions for  $\text{Ricci} > 0$  in the simply connected category are the same as for positivity of the scalar curvature.

Notice in this regard that Yau's celebrated solution of the Calabi conjecture provides many examples of (Kähler) manifolds with  $\text{Ricci} > 0$  which, as  $\dim W \rightarrow \infty$ , display a wide spectrum of "stable" homotopy types. On the other hand, there are elementary examples of closed manifolds with  $\text{Ricci} > 0$  and with arbitrarily large homotopy types (see [Sha-Ya], [Col]<sub>ARC</sub>).

(b) Our trick of taming the loop spaces by contracting the 1-skeleton of  $W$  to a point is not new. It already appears, as was pointed out to me by I. Babenko, in an old paper by Adams and Hilton (see [Ad-Hi]).

**7.4. Corollary:** *For two generic points  $x, y$  in  $W$ , the number of geodesic arcs from  $x$  to  $y$  of length less than  $t$  is at least*

$$\sum_{i=1}^{ct} b_i(X).$$

*The same inequality is true for periodic geodesics, provided that the metric has the (generic) property of being "bumpy" in the sense of [Abr].*

**Proof.** The condition that the metric be bumpy guarantees that all critical orbits of the energy function are nondegenerate. Thus, Morse theory (cf. [Klin], p. 63) shows that  $Y_t$  has the homotopy type of a CW complex having no cells of dimension  $p$  such that of geodesics of index  $p$  and length less than

$t$ . Thus, there are at least

$$\sum_{i=1}^{\infty} b_i(Y_t)$$

periodic geodesics of length less than  $t$ . By Theorem 7.3, however, we have  $b_i(Y_t) \geq b_i(Y)$  for  $i \leq ct$ , and the desired inequality follows.

**7.5. Remark:** Using connected sums, one can construct compact, simply connected manifolds  $W$  for which  $b_n(X)$  grows exponentially as a function of  $n$ . For any bumpy Riemannian metric on such a manifold, the number of geometrically distinct geodesic loops at a point grows exponentially with the length (and “bumpy” is probably unneeded in most cases).

**7.6. Remark:** Usually the condition that a metric be bumpy required by Corollary 7.4 is not satisfied by homogeneous spaces. When such spaces have a closed geodesic, they have families of closed geodesics. For manifolds all of whose geodesics are closed, see [Besse].

**7.6<sub>2+</sub>** **Remarks.** (a) The above implies that if  $b_i(X)$  grows exponentially, then the singular metric on  $\mathbb{R}^n = T_w(W)$  induced by the exponential map  $T_w(W) \rightarrow W$  has exponential volume growth. This, combined with Yomdin’s solution to the  $C^\infty$ -version of the *Shub entropy conjecture*, shows that the entropy of the geodesic flow for every  $C^\infty$  metric on such  $W$  has positive topological entropy (compare [Gro]Yom and [Bur–Pat]).

(b) All this suggests that having zero entropy of the geodesic flow and/or a slow (subexponential or less) volume growth of  $T_w(W)$ , with the metric induced from  $(W, g)$  by  $\exp_w : T_w(W) \rightarrow W$  severely restricts the geometry (as well as the topology) of  $W$ . But how severely? For example, can one classify in some sense the Riemannian manifolds  $(W, g)$  for which  $T_w(W)$  has polynomial growth of a given (e.g., small) degree  $d$  at every point  $w \in W$ ?

**7.7. Exercise:** Using Theorem 7.3, the reader can prove the following result of D. Kan (see [Kan]): Given a compact, simply connected manifold  $W$  via a triangulation, one can effectively compute the homotopy groups of  $W$ , showing in the course of this that they are finitely generated (where the actual effectiveness depends on a given contraction of the 1-skeleton of  $W$  to a point, compare [Serre]).

**7.8. Remark:** Theorem 7.3 can be immediately generalized to the case of a compact manifold whose fundamental group is finite by passing to

the universal cover. But, we can already see some restrictions on this generalization: Suppose that the conclusion of Theorem 7.3 is true for a manifold  $W$ . Then the word problem can be solved effectively in the fundamental group  $\pi_1(W, w)$ . Indeed, let us realize a word given by a loop  $\ell$  of length  $t$  in  $W$ , where  $W$  is described by a triangulation. It then suffices to consider loops in  $W$  of length less than  $Ct$  to decide whether  $\ell$  is homotopic to 0. In fact, it suffices to examine the list of loops consisting of  $C't$  edges of the triangulation and the contiguity relations among these loops (see [Span], Ch. 3, Sec. 6) which represents a finite number of operations. For this reason, if the word problem in  $\pi_1(W)$  is algorithmically unsolvable, then for every subrecursive function  $f(t)$  there exist contractible loops in  $W$  of lengths  $t_i \rightarrow \infty$  such that none of them can be deformed to a point by passing through loops of lengths  $\leq f(t_i)$  (where “recursive” for real  $t$  means  $\text{ent}(\text{ent}(f(\text{ent}(t))))$  recursive).

**7.8<sub>2+</sub><sup>1</sup> Dehn functions.** The minimal function  $f(t)$  such that every contractible loop in  $W$  can be homotoped to zero within loops of lengths  $\leq f(t)$ , is essentially (up to an obvious equivalence) determined by  $\pi_1(W)$  and may be called the *Dehn function* of the group  $\Pi = \pi_1(W)$ . Much work has been done recently to evaluate Dehn’s functions of specific groups  $\Pi$ , but it is nevertheless unknown for many rather elementary examples (see [Gersten]<sub>DF</sub>, [Gersten]<sub>II</sub>, [Gro]<sub>AI</sub> and the references therein). On the other hand, there is a general construction due to Rips and Sapir (unpublished) realizing “almost every” recursive function by the Dehn function of some group  $\Pi$  (compare [Brid], [Pap]<sub>SQH</sub>). This Dehn function is closely related to the optimal two-dimensional isoperimetric function  $I(t)$  from 6.32, and some people associate the name of Dehn with  $I(t)$  rather than with  $f(t)$ . We note here that, obviously,

$$f(t) = O(I(t)) \tag{*}$$

and

$$I(t) = O(\exp \exp f(t)), \tag{**}$$

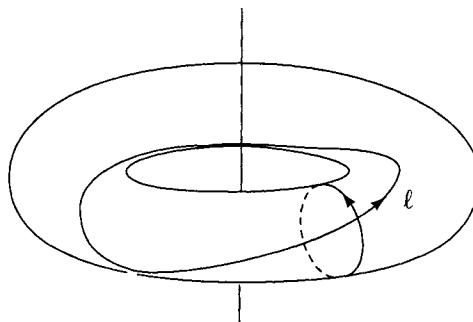
where (\*) easily improves to

$$f(t) = o(I(t)) \tag{**+}$$

for nonhyperbolic groups.

A closely related problem lies in finding groups  $\Pi$  with a controlled growth of the number  $N_t$  of contractible geodesics of length  $\leq t$ . Here there are examples of groups  $\Pi$  with sufficient complexity (Kolmogorov type) of the word problem to imply a lower bound  $N_t \geq \exp(\lambda t)$ ,  $\lambda > 0$ , for every  $W$  with  $\pi_1(W) = \Pi$ , (see [Nab]).

**7.9.** Corollary 7.4 proves the existence of many geodesics on a generic compact, simply connected manifold. For other cases in which the existence of closed geodesics is known, see [Gro–Mey], [Klin], [Sul–Vig]. Does there exist a closed geodesic in a given complete, noncompact, simply connected manifold? The answer is “yes” when the manifold is not contractible by the theory of Lusternik–Fet (see [Klin] and [Lus–Fet]). But if the manifold has no topology, then anything can happen. One way to proceed regardless of the topology is to consider metrics arising from compact quotients. For example, it is natural to ask whether a metric on  $\mathbb{R}^n$  that is induced by a metric on the torus and without closed geodesics is necessarily flat. The answer is “no” by the following example of Y. Colin de Verdière: The round 2-torus embedded in  $\mathbb{R}^3$  has no geodesic loops homotopic to 0. Indeed, such a loop  $\ell$ , if it is not a meridian, must intersect meridians transversally, since they are all geodesics. By continuity,  $\ell$  intersects all oriented meridians in the same sense, and so the number of intersections of the cycle defined by  $\ell$  and the cycle of the meridians is strictly positive or negative, so that  $\ell$  is not homotopic to zero.



**Problem:** Study closed Riemannian manifolds without contractible closed geodesics. Then isolate from among them those which, in addition, have a unique closed geodesic in every homotopy class.

## B. Dilatation of mappings between simply connected manifolds

Theorem 2.18 admits the following generalization:

**Theorem 7.10** *Let  $V, W$  be compact, simply connected Riemannian manifolds. If  $V$  has the rational homotopy type of a sphere, then the growth of*

$\#(D)$  (the number of homotopy classes of mappings from  $V$  into  $W$  containing a representative with dilatation less than  $D$ ) is polynomial. More precisely,  $\#(D) \leq CD^{\alpha(V,W)}$ , where  $\alpha$  depends only on the rational homotopy type of  $V, W$ .

**Remarks:** (a) The examples of 2.17 show that the simple connectivity (in fact, the finitude of  $\pi_1$ ) is essential.

(b) Of course, the constant  $C$  (about which we would like to know more) depends on the geometry of  $V, W$ .

We will prove the theorem in several steps. First, we note that it suffices to consider  $C^\infty$  mappings, since by [Dieu] every Lipschitz map  $f$  is homotopic to a  $C^\infty$  mapping whose dilatation is arbitrarily close to that of  $f$ .

**7.11.** The case when  $V = S^3$  and  $W = S^2$  indicates the general line of proof. Since the homotopy class  $[f]$  of  $f: S^3 \rightarrow S^2$  is determined by the Hopf invariant  $h(f)$ , it suffices to control  $h(f)$  as a function of the dilatation.

**7.12. Lemma:** *There is a constant  $C > 0$  such that for each  $f$ , we have  $h(f) \leq C(\text{dil}(f))^4$ .*

**Proof.** We recall the computation of  $h(f)$  in terms of differential forms, as described, for example, in [Godb], p. 221. Let  $\omega$  be a volume form on  $S^2$ , normalized by the condition  $\int_{S^2} \omega = 1$ . Its pullback  $f^*\omega$  is a closed 2-form on  $S^3$  and is therefore exact. If  $f^*\omega = d\alpha$ , the number

$$h(f) = \int_{S^3} f^*\omega \wedge \alpha$$

depends only on  $[f]$  and is an integer.

If, as in Proposition 2.11, we equip the space  $\Omega(S^n)$  of differential forms with the sup norm, we have

$$\|f^*\omega\| \leq C(\text{dil}(f))^2 \|\omega\|,$$

and the desired inequality is a consequence of a metrical Poincaré lemma formulated as follows.

**7.13. Lemma:** *There exists a constant  $C$  (depending on the metric on  $S^n$ ) such that for each closed form in  $\Omega^i(S^n)$  ( $0 < i < n$ ), there exists a form  $\alpha$  in  $\Omega^{i-1}(S^n)$  such that  $d\alpha = \omega$  and  $\|\alpha\| \leq C\|\omega\|$ .*

**Proof.** For a form  $\omega$  defined on an open subset of  $\mathbb{R}^n$  that is star-shaped relative to 0, the primitive given by

$$\alpha_x(\xi) = \int_0^1 \omega_x(tx, \xi) dt$$

satisfies such an inequality. From this remark, we obtain the proof from the fact that  $H^i(S^n; \mathbb{R}) = 0$  ( $0 < i < n$ ), as done in [Ber–Gost] for example (i.e., using differential forms), controlling the norm at each step.

**Some results of Chen–Sullivan (See [Fr–Gr–Morg], [Sul]<sub>DF</sub>, and [Sul]<sub>ICT</sub>)** By 7.11, the map  $f \mapsto h(f)$  defines a linear form on  $\pi_3(S^2)$  that can be expressed in terms of differential forms on  $S^2$ . More generally, if  $V$  is a simply connected manifold, the graded vector space  $\text{Hom}(\pi_*(V), Q)$  is isomorphic to  $M\Omega(V)/[M\Omega(V), M\Omega(V)]$ , where  $M\Omega(V)$  is the *minimal model* of the graded differential algebra  $\Omega(V)$  of differential forms on  $V$  defined as follows:

**7.15.** If  $A$  is a commutative-graded differential algebra (cf. [Leh], p. 18, or [Fr–Gr–Morg], Ch. 12) such that  $H^0(A) = \mathbb{R}$  and  $H^1(A) = 0$ , it can be shown (ibid) that there exists a commutative-graded differential algebra  $M$ , unique up to isomorphism, such that

1.  $M$  is a free algebra, i.e., it has no relations other than associativity and commutativity  $ab = (-1)^{\deg(a)\deg(b)}ba$ .
2.  $dM_n$  is contained in the subalgebra generated by the  $M_k$  such that  $k \leq n$  (here we denote by  $M_k$  the set of elements of degree  $k$ ).
3. There is a morphism  $\rho: M \rightarrow A$  of graded differential algebras that induces an isomorphism on cohomology.

**7.16. Examples:** The minimal model of  $\Omega S^{2n}$  is the free  $\mathbb{R}$ -algebra  $\mathbb{R}\{a, b\}$  generated by two elements  $a, b$  such that

$$\deg(a) = 2n \quad \deg(b) = 4n - 1 \quad da = 0 \quad db = a^2.$$

The element  $a$  gives  $H^{2n}$ , and the adjunction of the generator  $b$  of degree  $4n - 1$  kills the cohomology that the powers of  $a$  would give otherwise.

In contrast, the minimal model of  $\Omega(S^{2n+1})$  is simply  $\mathbb{R}\{c\}$  with  $\deg(c) = 2n + 1$ , where for reasons of parity  $c^2 = 0$  (cf. [Leh], Ch. 5).

**7.17. Minimal models and the Hopf invariant.** Under these assumptions, a  $C^\infty$  map  $f : S^3 \rightarrow S^2$  gives rise to the following commutative diagram (cf. [Leh], p. 19),

$$\begin{array}{ccc} M_{S^2} & \xrightarrow{\tilde{f}^*} & M_{S^3} \\ \rho \downarrow & & \downarrow \rho \\ \Omega S^2 & \xrightarrow{f^*} & \Omega S^3 \end{array}$$

From the properties of degree, it follows that  $\tilde{f}^* b$  is proportional to  $c$  and one can show (exercise or [Fr–Gr–Morg], p. 210) that  $\tilde{f}^* b = h(f)c$ .

**7.18. Proof of Theorem 7.10 for  $V = S^n$ .** We must extend the geometrical and algebraic considerations above to arbitrary simply connected manifolds. The minimal model of  $\Omega(W)$  is constructed step by step (cf. [Sul]ICT, p. 38, [Leh], p. 29, and [Fr–Gr–Morg], Ch. 12 for more details). Given a differential algebra  $M^n$  satisfying 7.15(1) and (2), and a morphism  $M^n \rightarrow \Omega(W)$  inducing an isomorphism of  $H^p M^n$  onto  $H^p(W; \mathbb{R})$  if  $p \leq n$ , and a surjection for  $p = n + 1$ , we obtain a new algebra  $M^{n+1}$  having the same properties up to stage  $n + 1$  by adjoining to  $M^n$  some generators of degree  $n + 1$  in order to kill the excess cohomology in  $H^{n+1} M^n$ .

Next, we must find an integral representation of  $\mathbb{R}$ -linear forms on  $\pi_n(W)$ . Given a representative  $f : S^n \rightarrow W$  of an element of  $\pi_n(W)$ , we begin with a system of representatives  $\omega_i$  for the deRham cohomology of  $W$  of degree less than or equal to  $n$ , and we consider their inverse images  $f^* \omega_i = \omega_i^*$ .

(a) For an  $n$ -form  $\omega_i$ , the integral  $\int_{S^n} \omega_i^*$  gives a linear form on  $\pi_n(W)$ . In this way, we obtain those forms that factor through the Hurewicz homomorphism (see 4.20 and [Hur–Wall], p. 148) to forms on  $H_n(W; \mathbb{Z})$ .

(b) If  $\deg(\omega_i) < n$ , then the form  $\omega_i^*$  is exact, so we can write  $\omega_i^* = d\alpha_i$  and consider all linear combinations  $\sum c_{ij} \omega_i \wedge \alpha_j$  that give closed forms. By the preceding discussion, these are the images under  $\rho$  of the generators of the minimal model of  $\Omega(W)$ . We integrate those of degree  $n$  over  $S^n$ . The others are exact, of the form  $d\alpha'_k$ , and we recommence with the combinations

$$\sum c'_{ik} \omega_i \wedge \alpha'_k.$$

After finitely many steps (since  $H^1(W; \mathbb{R}) = 0$ ), we obtain  $n$ -forms, which we integrate to show (cf. [Fr–Gr–Morg], Ch. 12, and [Sul]ICT, §11) that all linear forms  $L$  on  $\pi_n(W)$  are obtained in this way. It now suffices to

note that by Lemma 7.12, we have  $L(f) \leq c(\text{dil}(f))^r$ , where  $r$  depends essentially on the degree of the forms involved and the number of necessary steps.

*N.B.* A more careful examination of the above gives for  $r$  the bound  $2(n - 1)rg(\pi_n(W))$  (see [Gro]<sub>HED</sub>).

**7.19<sub>+</sub> Remarks.** (a) The method of minimal models applies to maps  $V \rightarrow W$ , where  $V$  is an arbitrary manifold, and this seems to bound the number of mutually nonhomotopic maps of dilatation less than  $d$  by  $d^r$  for some  $r$  depending on the rational homotopy types of  $V$  and  $W$ . (Actually, this appears to be obvious and my use of the word “seems” just reflects my reluctance to trust the intuition for minimal models which has grown rusty from years of nonuse.)

(b) One can use weaker dilatation measures of maps, such as the  $L_p$  norm of the differential of  $Df$  on  $T(V)$  or on some exterior power  $\bigwedge^i T(V)$  to evaluate the morphisms of the minimal models (see [Gro]<sub>HED</sub> and [Gro]<sub>CC</sub>).

(c) Instead of applying minimal models to general  $V$ , one could try an induction by skeletons of some triangulation of  $V$ , thus reducing the general case to that of the spheres. This approach, however, needs *a priori* bounds on the dilatation of homotopies contracting our spheres mapped to  $W$ . This point (which was overlooked in [Gro]<sub>HED</sub> and pointed out later to me by P. Pansu) is briefly discussed below.

**7.20<sub>+</sub> Basic problems of quantitative homotopy theory.** Topological spaces naturally appearing in the homotopy theory come along with particular metrics, or rather Lipschitz (or more general) classes of metrics. Such a class is essentially unique for spaces represented by finite polyhedra. Of course, two homotopy equivalent polyhedra  $P_1$  and  $P_2$  do not have to be bi-Lipschitz equivalent, but they are *Lipschitz homotopy equivalent* (in an obvious sense), and this is all we need. Next, if we look at the space of maps between two compact Riemannian manifolds  $V_1$  and  $V_2$ , for instance, this space  $\text{Map}(V_1 \rightarrow V_2)$  carries many (perhaps too many) natural (classes of) metrics coming from metrics on  $V_1$  and  $V_2$ . Here one can use the uniform metric between  $f_1, f_2: V_1 \rightarrow V_2$ , that is,

$$\text{dist}(f_1, f_2) = \sup_{v \in V_1} \text{dist}(f(v_1), f(v_2)),$$

but also more interesting metrics measuring the dilatations of homotopies  $h: V_1 \times [0, \ell] \rightarrow V_2$  between maps (where the choice of  $\ell$  may be important)

and also such characteristics of  $h$  as generalized Dirichlet functionals as

$$\int \| \wedge^i D| \wedge^i T(V_1 \times [0, \ell]) \| ^p$$

mentioned in (b) above. And also some infinite-dimensional classifying spaces have particularly nice geometric realizations (Grassmannian manifolds, spaces of operators on Hilbert space, etc.) with interesting metrics or even families of those.

Now, given any two metric spaces  $X$  and  $Y$ , we have a way to measure dilatation of maps  $f: X \rightarrow Y$  which may be our old friend the Lipschitz constant, or the dilatation of the  $k$ -volume or  $k$ -dimensional subsets, or something like a Dirichlet functional. Then we ask:

What is the asymptotic behavior of the number  $N(d_1)$  of maps  $f: X \rightarrow Y$  with “dilatation”( $f$ )  $\leq d$ ?

**Conjecture:** If  $X$  and  $Y$  are finite polyhedra with  $\pi_1(Y)$  finite, then  $N(d)$  is asymptotic to  $d^r$  for the (necessarily integral!) number  $r$  predicted by the computations with minimal models.

The problem here is to actually construct maps  $X \rightarrow Y$  with not very large dilatations in homotopy classes  $\rightarrow \infty$ .

A closely related problem is that of constructing a homotopy  $h: X \times [0, \ell] \rightarrow Y$  between two given maps  $f, f': X \rightarrow Y$  of “dilatation”  $\leq d$ , where we are given *a priori* knowledge of the existence of some  $h$ , and we want an  $h$  with a minimal possible “dilatation”  $\delta = \delta(d)$ . So, we have something here like the Dehn function, and we expect  $\delta(d) \sim d^\alpha$  for all simply connected finite polyhedra  $X$  and  $Y$ , and where quite often  $\alpha$  may be just equal to one. Finally, generalizing individual homotopies, we can look at the whole space of maps  $\mathcal{F} = \{f: X \rightarrow Y\}$  and study the asymptotics of the homotopy invariants of the levels of suitable geometric functionals on  $\mathcal{F}$  (such as dilatation) in the spirit of Morse theory. So, the possibilities are many (and one can easily imagine further questions along the same lines), but almost nothing is known beyond the results indicated in the sections above (see [Gro]<sub>NES</sub>, [Gro]<sub>CC</sub>, and [Gro]<sub>PCMD</sub> for further aspects of these problems).

**Example.** The first space to look at is  $\mathbb{C}\mathbb{P}^\infty$ . One knows that every map  $f: S^i \rightarrow \mathbb{C}\mathbb{P}^\infty$  is contractible for  $i \geq 3$ , and we want to estimate the necessary dilatation  $\delta$  of such a contraction  $h$  in terms of the dilatation  $d$  of  $f$ . The usual way to contract this  $f$  is by lifting it to the sphere  $S^\infty$  Hopf-fibered over  $\mathbb{C}\mathbb{P}^\infty$ . In other words, we take the induced  $S^1$ -fibration over  $S^i$ , say  $p: \Sigma \rightarrow S^i$ , where we look for a section  $\varphi: S^i \rightarrow \Sigma$  of a

small dilatation. We use the standard connection in the Hopf fibration  $S^\infty \rightarrow \mathbb{C}\mathbb{P}^\infty$ , which we pull back to  $p: \Sigma \rightarrow S^i$ . Next, we observe that the curvature of this equals the 2-form  $f^*(\omega)$  on  $S^i$  pulled-back from the canonical (Kähler) form  $\omega$  on  $\mathbb{C}\mathbb{P}^\infty$ . This  $f^*\omega$  has norm  $\approx d^2$  for  $d = \text{dil } f$ , and this allows a radial section in a hemisphere  $S_+^i \subset S^i$  with dilatation  $\approx d^2$ . Thus, for  $i \geq 3$ , two of these sections, one on  $S_+^i$  and the other on  $S_-^i$  can be joined by a “small” homotopy (essentially in  $S^1$ ) which gives us a section  $S^i \rightarrow \Sigma$  of dilatation  $\approx d^2$  and hence a contraction of  $f: S^i \rightarrow \mathbb{C}\mathbb{P}^2$  with dilatation  $\approx d^2$ . Probably, a (formal) generalization of this argument (to something like Postnikov towers) could yield the above conjecture along with a polynomial bound on the higher dimensional Dehn function  $\delta(d)$  for simply connected spaces.

# Chapter 8<sub>+</sub>

## Pinching and Collapse

### A. Invariant classes of metrics and the stability problem

**8.1.** The group of diffeomorphisms  $\text{Diff}(V)$  of a smooth manifold  $V$  naturally acts on the space of Riemannian metrics  $g$  on  $V$ ; various classes of metrics one studies in geometry are usually invariant under  $\text{Diff}(V)$ . In fact, we tend not to distinguish isometric manifolds, and a diffeomorphism  $f : V \rightarrow V$  establishes an isometry between  $(V, g)$  and  $(V, f^*(g))$  for each metric  $g$ . Furthermore, the geometric dictum “from local to global” suggests the study of *locally* defined classes of metrics on  $V$  which are moreover  $\text{Diff}$ -invariant.

**Example:** Fix a germ  $g_0$  of a Riemannian metric on a manifold  $V_0$  at a point  $v_0 \in V$  and consider the class  $\mathcal{G} = \mathcal{G}(g_0)$  of metrics  $g$  on  $V$ , where  $\dim V = \dim V_0$ , defined by the following condition: for each point  $v \in V$ , there exists an arbitrarily small neighborhood  $U \subset V$  of  $v$  isometric to  $(V_0, g_0)$  (i.e., to some neighborhood  $U_0$  of  $v_0$  in  $V_0$  where  $g_0$  is defined). In other words,  $(V, g)$  is *locally isometric* to  $(V_0, v_0, g_0)$  for every  $g \in \mathcal{G}$ .

**8.2. Theorem (Singer, see [Sing]).** *Let  $V$  be a  $C^\infty$ -smooth Riemannian manifold which is locally isometric to some  $(V_0, v_0, g_0)$ . Then  $V$  is locally homogeneous in the following sense: there exists a continuous function  $\varepsilon = \varepsilon(v) > 0$  on  $V$  such that the  $\varepsilon$ -balls  $B(v_1, \varepsilon(v_1))$  and  $B(v_2, \varepsilon(v_2))$  in  $V$  are mutually isometric for all  $v_1, v_2 \in V$ , where the implied isometry  $B(v_1, \varepsilon(v_1)) \leftrightarrow B(v_2, \varepsilon(v_2))$  sends  $v_1 \leftrightarrow v_2$ . Consequently, if  $V$  is complete and simply connected, then it is homogeneous, i.e., the isometry group is transitive on  $V$ .*

**8.3. Problem:** What is the minimal degree of regularity needed for the conclusion of the theorem to hold true? One knows that  $C^r$  with  $r \approx \dim V$  suffices (see [Gro]PDR, p. 165), but one may expect this for  $r = 0$  or even for rather general locally compact path metric spaces. (The difficulty stems from the possibility that the sizes of the mutually isometric  $\varepsilon$ -balls at  $v_1$  and  $v_2$  get smaller as  $\text{dist}(v_1, v_2) \rightarrow 0$ , since we do *not* assume *a priori* that our local isometries  $(U, v) \rightarrow (V_0, v_0)$  send  $v \rightarrow v_0$ . This problem becomes even more pronounced if we only require that for every neighborhood  $U_0 \subset V_0$  of  $v_0$ , where  $g_0$  is defined, there is a neighborhood  $U \subset V$  of  $v$  which admits an isometry onto an *open subset*  $U_1 \subset U_0$ . Notice that Singer's theorem applies in this case, thus showing that the new condition is as good as the old one for  $C^\infty$  metrics.)

**8.4. Example:** Fix a “curvature” tensor  $R$  on  $\mathbb{R}^n$ , i.e., a 4-tensor in the variables  $x, y, z, t$ , symmetric with respect to pairs, alternating in  $x \wedge y$  and  $z \wedge t$ , etc., (see [Kulk]), and consider the (class of) metrics whose curvature tensor lies in the  $O(n)$  orbit of  $R$  for every tangent space  $T_v(V)$ ,  $v \in V$ . The family thus obtained consists of those manifolds  $V$  whose curvature is constant, in the sense that for each  $v, w \in V$ , there exists an isometry  $i$  of  $T_v V$  onto  $T_w V$  such that  $i^* R_w = R_v$ . (The reader should not confuse this with the expression *constant curvature*, which means that the tensor  $R$  is of the form  $R(X, Y)Z = K(\langle Y, X \rangle Z - \langle X, Z \rangle Y)$ , nor with the stronger hypothesis of *parallel curvature*, or  $DR = 0$ , which characterizes symmetric spaces (see [Helg])). The manifolds in this family are *not all locally homogeneous* since there exist non-isometric manifolds having the same curvature (see [Fer–Kar–Munz] and [Tri–Van]).

**8.5. Existence, uniqueness, and stability of global developments of locally homogeneous spaces.** Let  $V_0$  be a *locally homogeneous path metric space* for which there is an  $\varepsilon > 0$  such that all  $\varepsilon$ -balls in  $V_0$  with centers sufficiently close (e.g.,  $\varepsilon$  close) to a given point  $v_0 \in V_0$  are all isometric to  $B_{v_0}(\varepsilon) \subset V_0$ , where we assume that the implied isometries  $B_v(\varepsilon) \leftrightarrow B_{v_0}(\varepsilon)$  move  $v \leftrightarrow v_0$  (which is automatic in many cases). Then we ask the following questions:

**I. Existence of a complete development.** Does there exist a *complete* metric space  $V$  locally isometric to  $V_0$  having all  $\varepsilon$ -balls  $B_v(\varepsilon) \subset V$  isometric to  $B_{v_0}(\varepsilon) \subset V_0$  with  $v \leftrightarrow v_0$ ? Such a space is called a *development* of  $V_0$ .

**Counterexample:** Let  $G$  be a compact, connected Lie group and let  $H_0$  be a connected *local* subgroup whose global development is *non-closed* in  $G$ .

Then the local quotient  $G_0/H_0$  usually admits no complete development.

**II. Homogeneity and uniqueness.** When is  $V$  homogeneous? unique up to isometry? Does *simple connectivity* ensure these properties?

The essential requirement needed for the uniqueness and homogeneity of the simply connected development is the uniqueness of extensions of local isometries (in  $V_0$ ), which is known to be satisfied by locally homogeneous topological manifolds by D. Montgomery's theorem, but there may exist some pathological infinite-dimensional counterexamples.

**III. Stability.** Now we arrive at the problem we are truly interested in. Suppose  $V'$  is a complete path metric space which is everywhere “locally close” to  $V_0$ . Is then  $V'$  “globally close” to some development  $V$  of  $V_0$ ?

To make sense of this, we need to specify the notion of local closeness. Here are several possibilities:

(A) There is an  $\varepsilon > 0$  such that all  $\varepsilon$ -balls in  $V'$  are  $\delta$ -close to  $B_{v_0}(\varepsilon) \subset V_0$  in one of our metrics, e.g., Hausdorff, Lipschitz, or  $\square_1$ , where  $\delta \leq \delta(\varepsilon)$  is small. Then, we naturally expect  $V'$  to be close to  $V$  in the same metric with the implied distance between  $V'$  and  $V$  going to zero as  $\delta \rightarrow 0$  for every fixed  $\varepsilon > 0$ .

(B) The same as in (A), but with  $\varepsilon = \varepsilon(v) > 0$  depending on  $v$  and with  $\delta = \delta(\varepsilon) > 0$  depending on  $\varepsilon$ .

(C) It may easily happen that even a space  $V_1$  locally *isometric* to  $V_0$  is not close to it in the sense of (A). In fact, we can divide a homogeneous space  $V$  by a discrete isometry group  $\Gamma$  which moves some points in  $V$  less than  $\varepsilon$ , thus creating small balls in  $V_1 = V/\Gamma$  non-isometric to those in  $V_0$ . For example, if we divide  $\mathbb{R}^n$  by a lattice  $\Gamma$  spanned by vectors of norm  $\leq \varepsilon_1 \sim \varepsilon/n$ , then each  $\varepsilon$ -ball in  $V_1 = \mathbb{R}^n/\Gamma$  is isometric to all of  $V_1$ , which is a torus whose geometry is far from that of a Euclidean ball  $B(\varepsilon) \subset \mathbb{R}^n$ . With this in mind, we modify (A) by requiring that for each  $v \in V'$ , there is a (possibly non-injective!) map  $e: B_{v_0}(\varepsilon) \rightarrow V'$  for our ball  $B_{v_0}(\varepsilon) \subset V_0$ , such that the path metric in  $B_{v_0}(\varepsilon)$  induced from  $V'$  is  $\delta$ -close to the induced  $V_0$  metric in  $B_{v_0}(\varepsilon)$ . Here “close” typically means Lipschitz close, i.e.,  $e$  is  $(1 + \delta)$ -biLipschitz with respect to  $V_0$  and  $V'$ -metrics. But one can invoke the Hausdorff (and/or  $\square_1$ ) metric as well. In the latter case, one could use a slightly different setting with an intermediate “ball”  $\tilde{B}_v$ , that is, a connected space coming equipped with a local homeomorphism  $\tilde{e}: \tilde{B}_v \rightarrow V'$  such that a distinguished point  $\tilde{v} \in \tilde{B}_v$  goes to a given point  $v \in V$  and  $\tilde{v}$  lies  $\varepsilon$ -far from the boundary of  $\tilde{B}_v$ . Here we refer to the

induced path metric  $\widetilde{\text{dist}}$  in  $\tilde{B}_v$  and “ $\varepsilon$ -far from the boundary” means that each  $\varepsilon'$ -ball in  $\tilde{B}_v$  with the center  $\tilde{v}' \in \tilde{B}_v$  positioned  $\delta$ -close to  $\tilde{v}$  is sent *onto* the  $\varepsilon'$ -ball in  $V'$  around  $\tilde{e}(\tilde{v}') \in V'$ , provided that  $\delta + \varepsilon < \varepsilon$ . We call such  $\tilde{B}_v \xrightarrow{\tilde{e}} V$  an (open)  $\varepsilon$ -multiball around  $v \in V'$  if in addition  $\widetilde{\text{dist}}(\tilde{v}, \tilde{v}') < \varepsilon$  for all  $\tilde{v}' \in \tilde{B}$ . Now, the condition “ $V'$  is locally close to  $V_0$ ” reads as (A) above with “ball” replaced by “multiball.”

**8.6. Obstructions to stability: Overgrown size and collapse.** Suppose  $V'$  is compact and  $\delta$ -close on the  $\varepsilon$ -balls to  $V_0$  as in (A) above. Then, if  $\delta$  is sufficiently small compared to the universal number of  $\varepsilon'$ -balls needed to cover  $V'$ , with  $\varepsilon'$  slightly smaller than  $\varepsilon$ , say  $\varepsilon' = \varepsilon/3$ , then in most cases one can show that  $V'$  is close to some development  $V$  of  $V_0$ . We shall discuss particular examples later on and indicate here what can go wrong if some of the conditions above are not met.

(i)  $V'$  is too big compared to  $\delta$ , for example,  $V'$  has large diameter and/or dimension. Then local errors of order  $\delta$  appearing in the course of an assembly of  $V'$  from  $\varepsilon$ -balls may accumulate to something of order  $\varepsilon \exp(N)$ , where  $N$  is the number of the balls needed to cover  $V'$ . This is closely related to another kind of instability, called *Ulam instability*. A (homogeneous) metric space  $V$  is called *Ulam stable* (compare §III.5 in [Ulam]) if every  $\delta$ -almost isometric self-mapping  $V \rightarrow V$  is  $\delta'$ -close to some isometry with  $\delta' = \delta'(\delta) \xrightarrow{\delta \rightarrow 0} 0$ . Here again, one should specify the meaning of “ $\delta$ -almost” and “ $\delta$ -close.” One knows, for example, that most symmetric spaces (essentially, with the exception of  $\mathbb{R}^n$ ,  $H^n$ , and  $CH^n$ ) are Ulam stable in the quasi isometric sense (see [Pan]CC, [Kle-Le], [Esk-Farb]), but one does not know if the Hilbert sphere is Ulam bi-Lipschitz stable (as was recently pointed out to me by V. Zoritch), and where the expected answer is “no.”

**Exercise:** Show that for every  $\varepsilon > 0$  and  $\delta > 0$ , there exists an  $N$ , an  $\varepsilon$ -net  $\Sigma$  in the unit sphere  $S^N \subset \mathbb{R}^{n+1}$ , and a  $\delta$ -almost isometric (i.e.  $(1 + \delta)$ -biLipschitz) map  $\Sigma \rightarrow S^N$  which is  $\rho'_0$ -far from any isometry, for some fixed  $\rho'_0$ , say  $\rho'_0 = 0.01$ . (*Hint:* Observe that random  $2N$ -vectors in  $S^N$  are almost mutually orthogonal for large  $N$  and recall the Kirschbraun theorem.)

(ii) Another obstruction which can bring even a small  $V'$  far from any development  $V$  of  $V_0$  is the phenomenon of collapse, where  $V'$  is locally close to  $V_0$  in the sense of (C) above, with multiballs and without having  $\varepsilon$ -balls close to  $B_{v_0}(\varepsilon) \subset V_0$  as required by (A). We call this phenomenon *collapse*, since it corresponds in many cases to  $V'$  being Hausdorff close to a space of dimension strictly less than  $\dim V'$ . Notice that such a  $V'$  can

be covered by relatively few  $\varepsilon$ -balls, but these are no good any more since they are not close to  $B_{v_0}(\varepsilon) \subset V_0$ . Of course, one could try smaller balls of radii  $\varepsilon' \subset \varepsilon$  in  $V'$  which are  $\delta$ -isometric to  $B_{v_0}(\varepsilon') \subset V_0$ , but then we have to overcome two problems:

- (a) The number of these balls needed to cover  $V'$  is large.
- (b) Being “ $\delta$ -almost isometric” is a cheaper condition for smaller balls than for the large ones. For example, all sufficiently small balls in a compact Riemannian manifold are almost isometric (i.e.  $(1 + \delta)$ -biLipschitz) to the Euclidean one, without making this manifold globally almost Euclidean in any sense. Thus, we need  $\delta = \delta(\varepsilon) \rightarrow 0$  for  $\varepsilon \rightarrow 0$ , but even this cannot offset the possible disruption of stability due to collapse. We have seen this in 3.11, where we could have, for example, a sequence of homogeneous spaces  $V_i = G/H_i$  where the groups  $H_i$  locally converge to some closed subgroup  $H$  in the ambient Lie group  $G$  without converging to  $G$  globally (i.e. Hausdorff converging to a subgroup  $\bar{H} \subset G$  with  $\dim \bar{H} > \dim H = \dim H_i$ ). Thus, one can have  $V'_i$  with local geometries converging to that of  $S^2 \times S^3$  (in the sense of multiballs from (C)) without being remotely close to  $S^2 \times S^3$  in the global sense.

We shall see later on that such collapse cannot happen if  $V'$  is 2 connected. But prior to this, we want to study collapse for general Riemannian manifolds  $V$  with bounded sectional curvature, say  $|K(V)| \leq 1$ , where “collapse” signifies some deviation of the local geometry of  $V$  from the Euclidean. First of all, we shall clarify basic families of noncollapsed manifolds with  $|K(V)| \leq \text{const}$ , which we start by briefly explaining the meaning of the sectional curvature  $K(V)$ .

## B. Sign and the meaning of curvature

**8.7. The Rauch theorem and equidistant deformations.** The simplest manifestation of curvature is expressed by the *Rauch comparison theorem*, which estimates how much the *exponential map*  $\exp_v : T_v(V) \rightarrow V$  deviates from being isometric in terms of  $K(V)$ . Recall that  $\exp_v$  sends each vector  $x$  in the tangent space  $T_v(V) = \mathbb{R}^n$ ,  $n = \dim V$ , to the end of the geodesic segment  $[v, v']$  in  $V$  issuing from  $v$  in the direction  $x$  and having  $\text{length}[v, v'] = \|x\|$ . For example, if  $|K(V)| \leq 1$ , then  $\exp_v$  is locally  $(1 + \delta)$ -bi-Lipschitz on the ball  $B_0(\rho) \subset T_v(V) = \mathbb{R}^n$  for all  $\delta$  and  $\rho$  satisfying  $\rho \leq 1$  and  $\delta \leq \rho^r$ , where “ $(1 + \delta)$ -bi-Lipschitz” amounts here to the bounds  $\|D\| \leq 1 + \delta$  and  $\|D^{-1}\| \leq 1 + \delta$  for the norms of the differential

of the map  $\exp_v$  and its inverse. The above is a rather rough bound, but it coveys the essence. In fact, one knows that the condition  $|K(V)| \leq 1$  makes

$$\|D_x\| \leq \sinh \|x\| \quad (*)$$

and

$$\|D_x^{-1}\| \leq 1/\sin \|x\| \quad (**)$$

for  $\|x\| \leq \rho = \pi$  (see [Che–Ebin] and below). In other words,  $(*)$  tells us that  $\exp_v$  *expands no more* than the exponential map in hyperbolic space, while  $(**)$  says that it *contracts no more* than  $\exp$  in the unit sphere. Thus, the condition  $|K(V)| \leq 1$  makes small multiballs in  $V$  almost Euclidean.

**Exercises.** (a) Show that  $K(V) \geq 0$  if and only if  $\|D\| = \|D(\exp_v(x))\| \leq 1$  for  $\|x\| \leq \varepsilon = \varepsilon(v) > 0$  and all  $v \in V$ , while the opposite inequality  $K(V) \leq 0$  is equivalent to  $\|D^{-1}\| \leq 1$  everywhere. (This will become clear with our definition of  $K(V)$  given below.)

(b) Show that the inequality  $K(V) \geq 0$  ensures the inequality  $\|D \exp_v(x)\| \leq 1$  insofar as the geodesic segment  $[v, v' = \exp_v(x)]$  *remains locally distance-minimizing*, i.e., such that every curve between  $v$  and  $v'$  lying close to  $[v, v']$  is longer than  $\text{length}[v, v'] = \|x\|$ . This minimizing condition is customarily expressed by saying that “*there are no conjugate points on the segment  $[v, v']$ .*”

(b') Similarly, prove that  $K(V) \geq 1$  makes  $\|D \exp_v(x)\| \leq \sin \|x\|$  in the absence of conjugate points on  $[v, v']$ , while the condition  $K(V) \geq -1$  makes  $\|D \exp_v(x)\| \leq \sinh(x)$  before the first conjugate point appears (along  $[v, v']$ ).

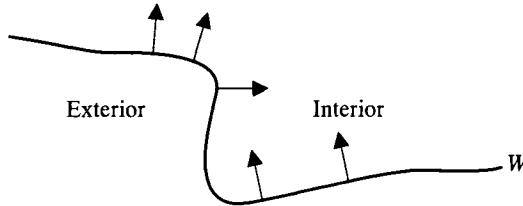
(c) Show that  $K(V) \leq 0$  makes  $D^{-1} \geq 1$  everywhere, that the condition  $K(V) \leq 1$  implies  $D^{-1} \leq (\sin \|x\|)^{-1}$  for  $\|x\| \leq \pi$ , and that  $K(V) \leq -1$  yields  $D^{-1} \leq (\sinh \|x\|)^{-1}$  everywhere. (Again, all of this will become perfectly clear by the end of this section.)

(d) The above geometric implications of the sign (and magnitude) of the curvature extend trivially to manifolds  $V$  for which  $K(V)$  is bounded (from above and/or from below) by a constant  $c \neq 1$  via the scaling  $V \mapsto \sqrt{c}V$ , since  $K(\sqrt{c}V) = cK(V)$ .

Although the Rauch theorem adequately reflects the bounds on  $K(V)$ , there are further geometric implications of these bounds which are hard to derive directly from the Rauch theorem. In fact, if we enlarge the category under consideration from Riemannian to Finslerian, then the properties of

$K(V)$  expressed by the Rauch theorem become inequivalent to stronger geometric manifestations of  $K(V)$  discussed below.

**Definition of  $K(V)$  via moving hypersurfaces.** Take a smooth, co-oriented hypersurface  $W \subset V$  and let  $W_t$ ,  $t \in [-\varepsilon, \varepsilon]$  be *equidistant* hypersurfaces, which are the levels of the signed distance function  $v \mapsto \pm \text{dist}(v, W)$  for which the + sign corresponds to what we call the *exterior* of  $W$ , and the - sign refers to the *interior*.



We denote by  $g_t$  the Riemannian metric on  $W_t$  induced by the metric  $g$  on  $V$ , and we bring this  $g_t$  to  $W_0 = W$  via the *normal projection*  $W_t \rightarrow W$ . Notice that for small  $\varepsilon$ , our function  $\pm \text{dist}(v, W)$  is smooth (away from the boundary of  $W$ ), thus the levels  $W_t$  are also smooth, since  $\|\text{grad} \pm \text{dist}\| = 1$  and the *normal projection* (or the gradient flow map) from  $W_t$  to  $W$ , for  $v \mapsto (\text{nearest point in } W)$ , is a diffeomorphism. We denote by  $g_t^*$  the metric on  $W$  coming from  $g_t$  by the normal projection, and we make the following

**Definition of the second fundamental form of  $W$ .** This is a quadratic differential form on  $W$ , denoted  $H$  and defined via the  $t$ -derivative of  $g_t^*$  on  $W$  by

$$H = H^W = \frac{1}{2} \frac{d}{dt} g_{t=0}^*. \quad (+)$$

If the reader is used to another definition, we invite him/her to check that it is equivalent to our (+). Note that one should only bother doing this in  $\mathbb{R}^n$ , since every Riemannian manifold is infinitesimally Euclidean at each point  $v$  up to first order. *Thus, all formal properties of curvatures of submanifolds in  $V$ , as well as those of (first and) second derivatives of functions on  $V$ , are the same for general Riemannian  $V$  as for  $V = \mathbb{R}^n$ .*

**Exercises:** (a) Recall that  $W$  is called *strictly convex* at  $w \in W$  if  $H_w > 0$ . Show that this is equivalent to the exponential pullback of  $W$  in  $\mathbb{R}^n = T_w(V)$  being strictly convex (in the Euclidean sense) at zero. Thus show that sufficiently small, closed, locally strictly convex *immersed* hypersurfaces in  $V$  are in fact *embedded* (i.e. have no double points) for  $n \geq 3$ , provided that “strictly” is uniform as “small”  $\rightarrow 0$ . (This may look trivial, but a similar problem in Finsler geometry appears to be unsolved.)

- (b) Show that the hessian of  $\pm \text{dist}(v, W)$  has rank  $n - 1$  with  $\ker \text{Hess} = \text{grad}(\pm \text{dist})$ , and with the eigenvalues at  $v \in W_t$  equal to those of  $\Pi_v^{W_t}$  with respect to  $g_t$ .

Now we want to define the curvature of  $V$  by comparing the second derivative of  $g_t^*$  to that of some  $W$  in Euclidean space. To do this, we introduce the *shape operator*  $A$  of  $W$ , which is the symmetric operator associated to  $\Pi$  via  $g_0$ , i.e., defined by

$$\Pi(\tau_1, \tau_2) = g_0(A\tau_1, \tau_2).$$

Thus,  $A: T(W) \rightarrow T(W)$ , and the eigenvalues of  $A$  are called the *principal curvatures* of  $W$ . A classical (going back to Gauss? Euler?) formula for  $W \subset \mathbb{R}^n$  reads

$$\frac{dA_t^*}{dt} = -(A_t^*)^2,$$

at  $t = 0$ , where  $A_t^*: T(W) \rightarrow T(W)$  is obtained from the shape operator  $A_t$  on  $W_t$  by the normal projection  $W_t \rightarrow W$ .

**Proposition-Definition.** *There exists a unique quadratic form  $B = B_S$  on each hyperplane  $S \subset T_v(V)$  such that every hypersurface  $W \subset V$  passing through  $v$  and having  $T_v(W) = S$  satisfies the following*

**Tube formula at  $v \in W$  with  $T_v(W) = S$ ,**

$$\frac{d}{dt} A_{t=0}^* = -(A_0^*)^2 + B_S. \quad (\star)$$

This  $B$  is related to the sectional curvature  $K_v$  by

$$K(\tau_1 \wedge \tau_2) = -g(B_S(\tau_1), \tau_2)$$

for all  $S \subset T_v(V)$  and all orthonormal vectors  $\tau_1$  and  $\tau_2$ , where  $\tau_1$  is normal to  $S$  (and hence  $\tau_2 \in S$ ).

The reader who prefers another definition of  $K$  may amuse him/herself by identifying his/her definition with ours. This will be a simple (albeit boring) linear algebraic computation for whatever alternative definition one wants to substitute for  $(\star)$ .

The efficiency of  $(\star)$  lies in its applicability to every hypersurface  $W_t$  in an equidistant family, insofar as they remain smooth. Thus, we can control the variation of  $\Pi^{W_t}$  and  $g_t$  with  $t$ .

**The traced tube formula and Ricci curvature.** The Ricci curvature is responsible for the second derivative of the  $(n - 1)$ -volume of  $W_t$  in the same way that the sectional curvature controls the induced metric. We

start again with the first derivative of the *volume density* on  $W_t$  (thought of as an  $(n - 1)$ -form on  $W_t$  stripped of its sign) and observe that

$$\frac{d \text{vol}_t^*}{dt} = M(W_t) \text{vol}_t^*.$$

Here,  $\text{vol}_t^*$  denotes the volume density of  $W_t$  brought to  $W_0$ , and  $M(W) = \text{Tr}_r II^W$ . This is elementary for  $V = \mathbb{R}^n$ , and the case of a general  $V$  follows by the preceding discussion. Then we trace  $(\star)$  and obtain

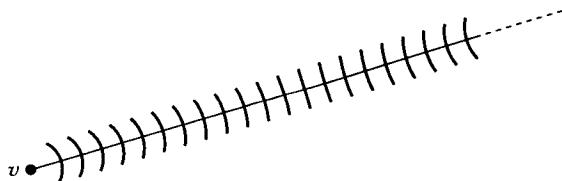
$$\frac{d}{dt} M(W_t) \stackrel{(\star)}{=} -\text{Tr} A_t^2 - \text{Ricci}(\nu, \nu), \quad (\star) \text{Tr}$$

where  $\nu$  is the unit normal (inward or outward makes no difference) field on  $W_t$ , and Ricci is the quadratic form defined by

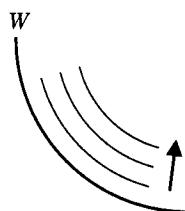
$$\text{Ricci}(\nu, \nu) = \text{Tr} B_S,$$

where  $\nu$  is normal to  $S \subset T(V)$  for all hyperplanes  $S$ .

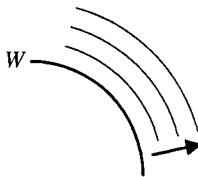
**Exercises:** (a) Recapture the Rauch theorem by applying  $(\star)$  to the concentric spheres around each point  $v \in V$  or rather to germs  $W_t$  of these spheres normal to each geodesic segment issuing from  $v$  before the first conjugate point (which is equivalent to smoothness of these germs).



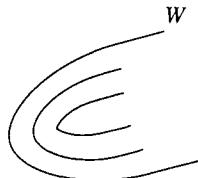
(b) Show that  $K \geq 0$  is equivalent to the preservation of (strict) convexity under the inward deformations of  $W$ ,



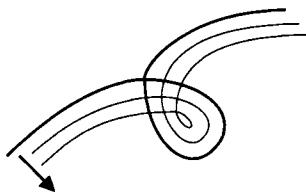
while  $K \leq 0$  corresponds to preservation of convexity for outward deformations.



Show furthermore that if  $K \geq 0$ , then the convexity is preserved for inward deformations even after  $W_t$  loses the smoothness, where the (strict) convexity of a nonsmooth hypersurface  $W$  can be defined with the exponential pullbacks of  $W$  to  $\mathbb{R}^n = T_v(V)$  as before. Then prove *Gromoll's contraction principle*, which claims that a compact manifold  $V$  with nonempty convex boundary  $W$  and  $K(V) > 0$  contracts to a point by a family of such submanifolds  $(V_t, W_t)$ . In particular,  $V$  is homeomorphic to the  $n$ -ball.



- (c) Study inward equidistant deformations of closed, strictly convex *immersed* hypersurfaces  $W$  in complete manifolds  $V$  with  $K(V) \geq 0$ , and show that they remain immersed strictly convex (although they may become singular) for  $\dim W \geq 2$ . (The idea of the proof, suggested to me by W. Meyer more than 20 years ago, consists in excluding bad local singularities like those appearing for  $\dim W = 1$  by analyzing what happens in  $\mathbb{R}^n$ , where everything is rather transparent.)



- (d) Prove the Cartan-Hadamard theorem, which claims that a *complete, simply connected manifold  $V$  with  $K(V) \leq 0$  is diffeomorphic to  $\mathbb{R}^n$* ,  $n = \dim V$ , by appealing to the convexity of the concentric spheres around some point.

- (e) Assume  $V$  is complete and noncompact, and show that  $V$  admits a

*horofunction* (generalizing the idea of *Busemann functions*), which is a limit

$$h(v) = \lim_{v_i \rightarrow \infty} (\text{dist}(v, v_i), \text{dist}(v_0, v_i))$$

for some points  $v_i \rightarrow \infty$ . Show that every horofunction is smooth and *convex* (i.e.,  $\text{Hess}(h) \geq 0$ ) if  $\pi_1(V) = 0$  and  $K(V) \leq 0$ . (On the other hand, it is concave and possibly nonsmooth when  $K \geq 0$ .) Furthermore, if  $K(V) \leq -1$ , then  $\text{div}(\text{grad}(h)) \geq n - 1$ , which combined with Stokes' formula yields the isoperimetric inequality in such  $V$ , as was mentioned earlier.

We refer the reader to the survey [Gro]sign for a more comprehensive account of the geometric effect of the sign of the curvature, while here we turn to the problem of collapse.

## C. Elementary geometry of collapse

**8.8.** If we deal with manifolds  $V$  with bounded curvature, say  $|K(V)| \leq 1$ , then there is no ambiguity about what collapse means: either at some point  $v \in V$  the exponential map  $\exp_v : T_v(V) = \mathbb{R}^n \rightarrow V$  is injective on a large, or rather, not on a very small ball  $B_0(\rho)$ , i.e. for  $\rho$  comparable to 1, or the exponential map loses injectivity on a small  $\rho$ -ball in  $T_v(V) = \mathbb{R}^n$ . In the first case, going under the heading of “injectivity radius of  $V$  at  $v$  is  $\geq \rho$  for  $\rho \approx 1$ ,” we say that  $V$  is noncollapsed at  $v$ , and if the *injectivity radius*, denoted  $\text{InjRad}_v(V)$  (defined as the maximal  $\rho$  where  $\exp$  is injective) is small, much smaller than one, we say  $V$  is collapsed at  $v$ . To be precise, we must specify what is small and what is large, which can often be ambiguous. A simple way out is to deal with sequences of manifolds  $(V_i, v_i)$  with  $|K(V_i)| \leq 1$  where noncollapse signifies

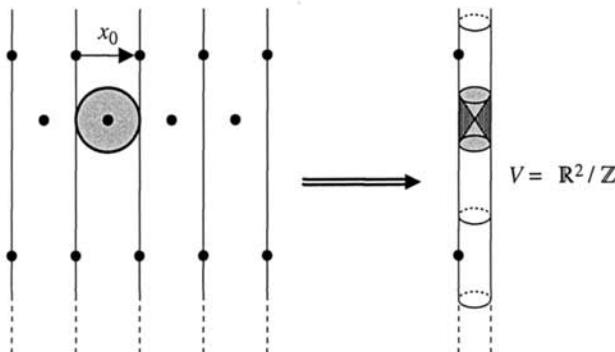
$$\text{InjRad}_{v_i}(V_i) \geq \rho > 0 \quad (\text{No-Co})$$

for  $i = 1, 2, \dots$ , while collapse refers to

$$\text{InjRad}_{v_i}(V_i) \rightarrow 0 \quad (\text{Co})$$

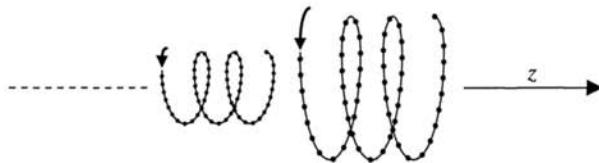
as  $i \rightarrow \infty$ . By passing to a subsequence, one always falls into one of these two possibilities, either (No-Co) or (Co).

**8.9. Basic flat example.** Let  $V = \mathbb{R}^n / \Gamma$  for some isometry group  $\Gamma$  freely acting on  $\mathbb{R}^n$ , and look at  $V$  at the point  $v_0$  corresponding to  $0 \in \mathbb{R}^n$ . The easiest case is where  $\Gamma$  acts by parallel translation, say  $\Gamma$ , generated by a single  $\gamma$  moving  $x \mapsto x + x_0$ .



Here, collapse progresses as  $\|x_0\| \rightarrow 0$ , where the cylinder  $V = \mathbb{R}^n/\mathbb{Z}$  Hausdorff converges to  $\mathbb{R}^{n-1}$ . And the injectivity radius of  $V$  equals  $\|x_0\|/2$  at all  $v \in V$ .

A more interesting picture arises with a single isometry  $\gamma$  on  $\mathbb{R}^3$  which acts on  $(x, y, z)$ -space  $\mathbb{R}^3$  by translating the  $z$ -axis along itself by  $2\rho$  and by rotating the  $(xy)$ -plane by  $\alpha$ . The orbit of different points here have different geometries. Points in the  $z$ -axis remain there to form just a copy of straight  $\mathbb{Z}$ , while the points away from the  $z$ -axis spiral about it. The specifics depend on the relative sizes of  $\rho$  and  $\alpha$ , as well as on the distance from the  $z$ -axis.



The injectivity radius of  $V$  at the points  $v$  on the closed geodesic  $S \subset V$  corresponding to the  $z$ -axis equal  $\rho$ , and it increases as  $v \in V$  goes away from  $S$ . In fact, the displacement by  $\gamma$  of a point  $\tilde{v} \in \mathbb{R}^3$  within distance  $d$  from the  $z$ -axis is approximately  $d\alpha + \rho$ . This may convey the wrong impression that the injectivity radius there is of the order at least  $d\alpha$  no matter how small  $\rho$  is. However, as we go far from the  $z$ -axis, the minimal displacement of  $\tilde{v}$  is caused not by  $\gamma$  but rather by some  $\gamma^p$ ,  $p > 1$ , which turns around the  $z$ -axis and comes back closer to  $\tilde{v}$  than to  $\gamma(v)$ . For example, in the limit case where  $\rho = 0$ , every point  $\tilde{v} \in \mathbb{R}^3$  rotates by an angle  $\alpha$  remaining in a fixed circle around the  $z$ -axis. Thus, some power  $\gamma^p(\tilde{v})$  comes arbitrarily close to  $\tilde{v}$ . In general, to see what happens, we evaluate the volume of a ball  $B_v(R) \subset V$ . We denote by  $N_v(R)$  the number of points of the orbit of  $\tilde{v} \in \mathbb{R}^3$  over  $v$  in the Euclidean  $R$ -ball around  $\tilde{v}$  and

observe that  $\text{vol } B_v(R) \approx R^3/N_v(R)$ , provided that  $R$  is significantly larger than  $r = \text{InjRad}_v(V)$ , say  $R > 100r$ . On the other hand, the number  $N_v(R)$  is pinched roughly between  $N_{\min} = R/2r$  and  $N_{\max} = R^3/r^3$ . Indeed, the minimal distance between the points in the orbit of  $\tilde{v}$  equals  $2r$ , and so we must have at least  $R/2r$  points in the orbit before it leaves the ball  $\tilde{B}_{\tilde{v}}(R) \subset \mathbb{R}^3$  starting from the center. (Notice that every orbit eventually goes to infinity in  $\mathbb{R}^3$  as the action has no fixed point.)

On the other hand,  $N(R)$  cannot exceed the number of disjoint  $r$ -balls in  $\tilde{B}(R)$ , and the  $r$ -balls around the orbit points are disjoint, which makes  $N(R) \leq R^3/r^3$  by the obvious volume count. It follows that  $\text{vol } B_v(R) \geq r^3$ , which is obvious anyway, since the  $r$ -ball  $B_{\tilde{v}}(r)$  with  $r \leq \text{InjRad}_v(V)$  injects into  $V$  under the map  $\mathbb{R}^3 \rightarrow V$  by the very definition of the injectivity radius. (In fact, a little thought shows that  $\text{vol}_v(B_v(R)) \geq r^2 R$  in our case, since the diameter of  $B_v(R)$  is at least  $R$ .) Now, let  $d = \text{dist}(v, S)$ , so that  $B_v(R) \subset B_{v_0}(d+R)$  for  $v_0 \in S$ . The volume of  $B_{v_0}(d+R)$  is approximately  $\rho(d+R)^2$  (where  $\rho = \text{InjRad}_{v_0} V$ ,  $v_0 \in S$ ), and so

$$r^3 = (\text{InjRad}_v(V))^3 \leq \text{vol } B_v(R) \leq \rho(d+R)^2.$$

We choose  $R = d$  and conclude that the upper bound on  $r$  in terms of  $d = \text{dist}(v, S)$  is

$$r \leq (\rho d^2)^{1/3}.$$

In particular, if the injectivity radius  $\rho$  is small at  $v_0$ , it remains small at all  $v \in V$  not too far from  $v_0$ . We shall see below that the dependence of  $\text{InjRad}_v V$  on  $v \in V$  persists for all  $V$  under the condition  $|K(V)| \leq 1$ .

**8.10. Lemma:** *Let  $V$  be a complete Riemannian manifold with  $|K(V)| \leq 1$  and  $\text{InjRad}_v(V) = \rho \leq 1$ . Consider the exponential map  $\exp_v$  from the  $R$ -ball  $\tilde{B}_0(R) \subset \mathbb{R}^n = T_v(V)$  to  $V$  for  $R \in [\rho, 1]$ . Then*

- (a)  $\text{card}(\exp_v^{-1}(v)) \geq R/\rho$ .
- (b)  $\text{card}(\exp_v^{-1}(v')) \geq (R-d)/\rho$  for  $d = \text{dist}(v, v')$  and all  $v' \in V$ .
- (c)  $\text{vol } B_v(R) \leq \text{const}_n \rho R^{n-1}$ .

**Proof.** We equip the ball  $\tilde{B} = \tilde{B}_0(R)$  with the Riemannian metric induced by  $\exp_v$  from  $V$ , so that  $\exp_v: \tilde{B} \rightarrow V$  becomes locally isometric. We claim that this  $\exp_v$  behaves like the restriction of a Galois covering map  $\tilde{V} \rightarrow V$  to an  $R$ -ball in this ghost covering  $\tilde{V}$ . Namely, we claim that there is a *pseudogroup*  $\Gamma$  of fixed-point free isometries operating on  $\tilde{B}$  such that  $\tilde{B}/\Gamma$  corresponds to the ball  $B_v(R) \subset V$ . This means that each  $\gamma \in \Gamma$  acts by a *partial* isometry on  $\tilde{B}$ , such that whenever the domain of definition  $D_\gamma \subset \tilde{B}$  of  $\gamma$  contains a point  $\tilde{v}$ , it also contains the  $r$ -ball  $B_{\tilde{V}}(r) \subset \tilde{B}$

for  $r = \min(\text{dist}(\tilde{v}, \partial\tilde{B}), \text{dist}(\gamma(\tilde{v}), \partial\tilde{B}))$ , where we note that  $\text{dist}(v, \partial\tilde{B}) = R - \text{dist}(\tilde{v}, \tilde{v}_0)$  for the center  $\tilde{v}_0$  of  $\tilde{B}$  and all  $\tilde{v} \in \tilde{B}$ . Then we have the usual rules: if  $\gamma_1$  is defined at some  $\tilde{v}_1 \in \tilde{B}$ , i.e.  $\tilde{v}_1 \in D_{\gamma_1}$  and  $\gamma_2$  is defined at  $\gamma_1(v_1)$ , then  $\gamma_2\gamma_1$  is defined at  $v_1$  and sends it to  $\gamma_2\gamma_1(v_1) = \gamma_2(\gamma_1(v_1))$ . All this is shown as in the corresponding standard proof of these properties for coverings with two points kept in mind:

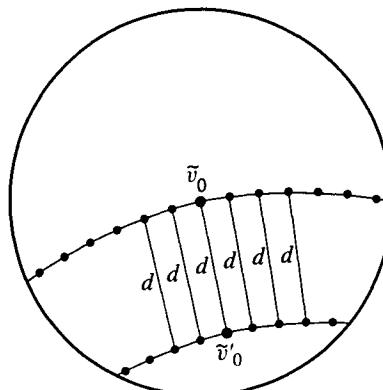
- I. The path covering property holds true for our “partial covering” map  $\tilde{B} \rightarrow V$  insofar as the paths in question do not reach the boundary  $\partial\tilde{B}$  of  $\tilde{B}$ . Thus we have covering paths in  $\tilde{B}$  issuing from  $\tilde{v} \in \tilde{B}$  as long as the lengths of these paths do not exceed  $R - \text{dist}(\tilde{v}_0, \tilde{v})$ .
- II. The ball  $\tilde{B}$  with the metric induced from  $V$  is *geometrically simply connected*. In fact, there is a canonical homotopy between any two paths in  $\tilde{B}$ , since *every two points in  $\tilde{B}$  can be joined by a unique geodesic segment* (see (5) below).

Granted I and II, we do have our pseudogroup  $\Gamma$  acting on  $\tilde{B}$ , where the  $\Gamma$ -orbits in  $\tilde{B}$  identify with the  $\exp_v$  pullbacks of points in  $V$ . (Here the reader should recall the elementary theory of covering spaces and replay it in the framework given by I and II.)

Now, to prove (a), we must show that the  $\Gamma$ -orbit of  $\tilde{v}_0$  reaches the boundary of  $\tilde{B}$ . Indeed, we could otherwise take a minimal (radius) ball  $B_{\tilde{v}'}(R') \subset \tilde{B}$  containing this orbit. Such a ball is unique (see (5) below), and so its center  $\tilde{v}'$  would be fixed under  $\Gamma$  contrary to the freedom of the action of  $\Gamma$ . Thus, we have

$$\text{card } \exp_v^{-1}(v) = \text{card } \Gamma)(\tilde{v}_0) \geq R/r,$$

and the inequality (b) for  $\Gamma(\tilde{v}')$  is clear from the picture.



Finally, we have (c), since  $\text{vol } \tilde{B} \simeq \mathbb{R}^n$  and  $\tilde{B}$  covers the ball  $B_v(R/2) \subset V$  with multiplicity at least  $R/2\rho$ . This bounds  $\text{vol}(B_v(R/2))$ , and then the bound on  $\text{vol } B_v(R)$  follows by Bishop's inequality.

**8.11.** *Let  $V$  be a complete manifold (possibly) with convex boundary where no geodesic segment of length  $\leq \ell$  contains a conjugate point. Then every geodesic 2-gon consisting of two segments of lengths  $\leq \ell$  can be homotoped to a closed geodesic in  $V$ .*

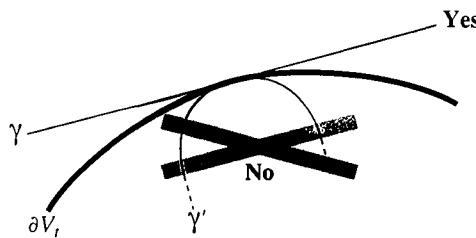
**Proof.** There is an obvious homotopy diminishing the lengths of the sides of the 2-gon,



which keeps diminishing the length unless we arrive at a closed geodesic. (This fails in the presence of conjugate points, as is seen for a pair of geodesic segments joining two opposite points on  $S^n$ .)

**8.12.** *Let  $V$  be a Riemannian manifold exhausted by a continuously increasing family of compact submanifolds  $V_t$ ,  $t \in [0, 1]$ , with strictly convex boundaries,  $V = \bigcup_{t=0}^1 V_t$ , where  $V_0 = \{v_0\}$ . Then  $V$  contains no closed geodesic  $\gamma$ .*

**Proof.** Take the minimal  $V_t$  containing  $\gamma$  and observe that the boundary of this  $V_t$  would meet  $\gamma$ , which is clearly impossible.



**8.13. Corollary:** *Let  $K(V) \leq 1$  and consider the unit ball  $\tilde{B} = \tilde{B}(1) \subset \mathbb{R}^n = T_v(V)$  with the Riemannian metric induced by  $\exp_v$  from  $V$ . Then every two points in  $\tilde{B}$  are joined by a unique geodesic segment in  $B$ .*

**Proof.** A pair of segments between  $\tilde{v}$  and  $\tilde{v}'$  in  $\tilde{B}$  could be deformed to a closed geodesic in  $\tilde{B}$ , which contradicts (4).

(6) *Let  $V$  be a complete manifold (possibly) with convex boundary where*

*every ball of radius  $\leq R$  has strictly convex boundary. Then every subset  $V_0 \subset V$  of diameter  $\leq R$  is constrained in a unique ball of minimal radius denoted  $B_{v_0}(R_0) \supset V_0$ .*

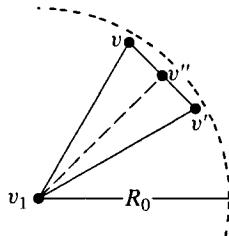
**Proof.** If  $V_0$  is contained in the intersection  $B_v(R_0) \cap B_{v'}(R_0)$ , then it lies in a smaller ball with center  $v''$  between  $v$  and  $v'$ , since the inequalities

$$\text{dist}(v, v_1) \leq R_0 \quad \text{and} \quad \text{dist}(v', v_1) \leq R_0$$

imply

$$\text{dist}(v'', v_1) < R_0$$

for the center  $v''$  of the minimal segment  $[v, v'] \subset V$  (where the uniqueness of the minimizing segments follows from the convexity of the balls).

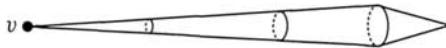


**8.14. Remarks.** (a) The properties (a) and (b) in 8.11 need only  $K(V) \leq 1$  (but not  $K(V) \geq 1$ ), as follows from our argument which relies at this point only on the convexity of the balls in  $\tilde{B}$ .

(b) Property (c) in 8.11 can be restated and proved under the assumption  $K(V) \leq 1$  with a suitably modified notion of the injectivity radius.

(c) One could prove (a) and (b) in 8.11 using only the Rauch theorem without any appeal to the convexity considerations. In fact, all one needs is the existence of a multiball  $\tilde{B} \rightarrow V$  of radius  $R$  around  $v$  whose metric (induced from  $V$ ) is (bi-)Lipschitz close to the Euclidean one. (We suggest that the reader work out the precise statement and proof.)

(d) Lemma 8.11 shows that there is an abrupt change in the behavior of the function  $r \mapsto \text{vol}_v(B(r))$  in the presence of collapse: it switches from the growth  $\simeq r^n$  to something slower than  $r^{n-1}$  for  $r$  crossing the threshold of  $\text{InjRad}_v(V)$ . For example, one cannot have  $\text{vol } B_v(r) \simeq \varepsilon r^n$  for a very small fixed  $\varepsilon$  and  $r \rightarrow 0$  if  $|K(V)| \leq 1$ . On the other hand, this is possible for  $K(V) \leq 1$ , where the borderline between collapse and noncollapse is fuzzier than for  $|K(V)| \leq 1$ .



**8.15. Variation of  $\text{InjRad}_v(V)$  with  $v \in V$ .** If  $|K(V)| \leq 1$ , then the injectivity radius  $r$  at  $v' \in V$  can be bounded in terms of  $\rho = \text{InjRad}_v(V)$  and  $d = \text{dist}(v, v')$  as follows

$$r \leq \text{const}'_n (\rho(d+1)^{n-1} \exp(n(d+1)))^{1/n} \quad (**)$$

in the range  $0 \leq \rho \leq 1$  and  $0 \leq r \leq 1$  (where the latter means that  $(**)$  is not applicable if its right hand side is  $\geq 1$ ).

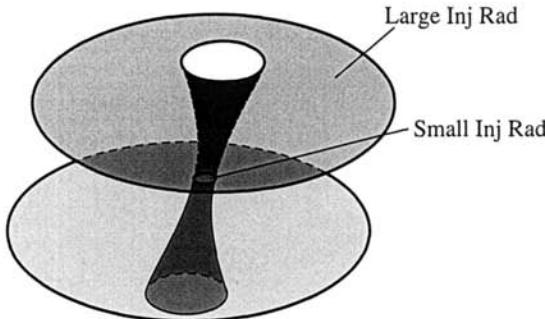
**Proof.** The  $(d+r)$ -ball around  $v$  satisfies

$$\text{vol}_v B(d+r) \leq \text{const}_n \rho(d+r)^{n-1} \exp(n(d+r)),$$

as follows from (c) in (2) and Bishop's inequality. On the other hand, the  $r$ -ball at  $v'$  has volume  $\geq r^n$ . Thus,  $(**)$  follows from the inequality  $\text{vol } B_{v'}(r) \leq \text{vol } B_v(d+1)$  for  $r \leq 1$ .

The meaning of  $(**)$  is that collapse of  $V$  at a single point implies it everywhere in  $V$ .

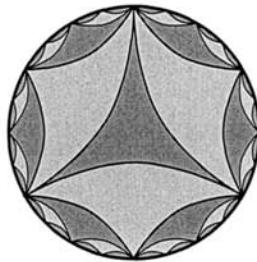
**8.16. Remarks.** (a) One could *define* collapse at  $v$  by requiring that the balls  $B_v(R) \subset V$  have volumes significantly smaller than  $R^n$ , and then the above would hold under the assumption  $\text{Ricci} \geq -(n-1)$  (or just the doubling property for balls, see below). On the other hand, this is not so if we allow  $\text{Ricci} \rightarrow -\infty$ , as the following picture shows.



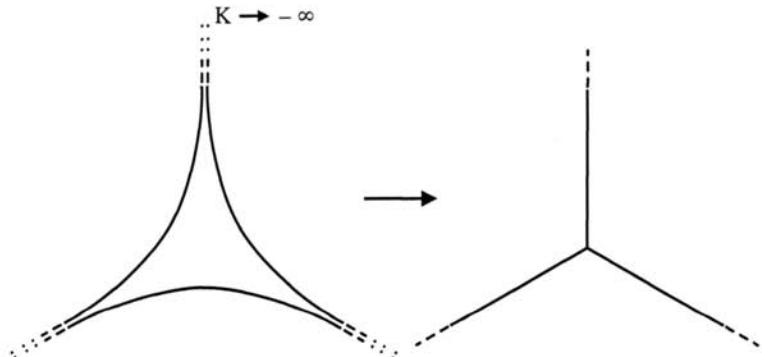
(b) Actually, our definition of collapse via  $\text{InjRad} \rightarrow 0$  was solely adjusted to the bound  $|K(V)| \leq -1$ . In general, the collapse can (and should) be defined by a more appropriate condition which must be stable under small perturbations in a reasonable moduli space of manifolds, e.g., in the

Lipschitz metric (where  $\text{InjRad}$  is highly discontinuous), and which must express some closeness of  $V$  to a space of dimension  $< \dim V$ .

**Example:** A good intuitive measure of such collapse is the Uryson width or  $\text{diam}_{n-1} V$ . On the other hand, complete, simply connected manifolds  $V$  with  $K(V) \leq -1$  which are as far from Uryson collapse as anything can be, still converge to something 1-dimensional if  $K(V) \rightarrow -\infty$ . For example, if  $\dim V = 2$ , then one can subdivide  $V$  with  $K(V) \leq \varepsilon < 0$  into ideal triangles,



and every such triangle converges to an infinite tripod for  $K \rightarrow -\infty$ .



Thus,  $V$ 's converge to a tree made out of a continuum of such tripods glued together.

**8.17. Collapse for  $\text{Ricci} \geq -1$ .** Let us look more closely at the *volume collapse on the scale  $R$*  defined by

$$\text{vol } B(R) \leq \delta R^n$$

for a given small  $\delta$ . This condition propagates from  $R$  to larger scale by Bishop's theorem (with  $\delta$  growing somewhat with  $R$ ) and, on the other hand, this *volume collapse* implies *Uryson collapse* by the following

**Theorem:** *There is a critical value  $\delta(n) > 0$  such that the inequality  $\text{vol } B_v(R) \leq \delta(n)R^n$  at all points  $v \in V$  implies that the  $(n - 1)$ -th Uryson width (or diameter measuring the distance of our  $n$ -dimensional  $V$  from an  $(n - 1)$ -dimensional polyhedron) satisfies*

$$\text{diam}_{n-1}(V) \leq 7R,$$

*provided that  $V$  is a complete manifold with  $\text{Ricci} \geq -1$ .*

**Proof.** Use our old map  $\Phi: V \rightarrow Q$  to the nerve  $Q$  of a covering of  $V$  by  $R$ -balls (see 5.33). Then, as was explained in 5.33, the local volume bound allows one to push this map to the  $(n - 1)$  skeleton  $Q_{n-1} \subset Q$  and thus obtain a map  $V \rightarrow Q_{n-1}$  with the diameters of the pull-back of all points bounded by  $7R$  (where 7 is for safety).

Notice that the bound on  $\text{diam}_{n-1} V$  (trivially) gives us a similar bound on the filling radius of  $V$ , and this is known to be large for some  $V$ . For example, it is infinite for the universal covering of compact aspherical manifolds and more generally of essential manifolds.

**Corollary:** *Let  $V$  be a compact essential (e.g., aspherical) manifold with  $\text{Ricci} \geq -1$  and with fundamental group in the class  $\mathcal{G}_C$  of 5.23 with  $c \geq c_0 \geq 0$ . Then there exists a point  $v \in V$  with*

$$\text{vol } B_v(1) \geq \text{const} = \text{const}(n, \text{diam } V, c_0) > 0.$$

**Proof.** Take the point  $\tilde{v} \in \tilde{V}$ , where a ball  $B_{\tilde{v}}(r) \subset \tilde{V}$  injects to  $V$  with  $r > c$  (see 5.24) and observe that the volumes of all balls in  $\tilde{V}$  are bounded in terms of a single one, and the diameter of  $V$  by Bishop's theorem.

**Questions.** (a) Is it essential to have  $\text{Ricci} \geq -1$  in the above theorem? Probably there are (by necessity rather complicated) examples where the volume collapse is *not* accompanied by Uryson (or filling radius) collapse, but still some condition much weaker than  $\text{Ricci} \geq \text{const}$  may ensure the validity of the theorem.

(b) Can one make the const above independent of  $\text{diam } V$  and/or of  $c_0$ ? One knows, for example, that if all balls in  $V$  are small, then the simplicial volume  $\| [V]_D \|$  vanishes (see [Gro]vBC), which provides the positive answer in many cases.

## D. Convergence without collapse

**8.18.** Consider the class of Riemannian manifolds  $V$  of dimension  $n$  distinguished by the conditions

$$|K(V)| \leq C < \infty$$

and

$$\text{InjRad}_v(V) \geq \rho > 0.$$

We claim that the Hausdorff and the Lipschitz metrics  $d_H, d_L$  on the moduli space of such  $V$ 's are essentially equivalent (compare [Che]Fin). Namely,

**8.19.** *If  $d_H(V, V') \leq \delta$  in our class, then the Lipschitz distance is also small  $d_L(V, V') \leq \Delta$  for  $\Delta = \Delta(\delta, C, \rho) \rightarrow 0$  as  $\delta \rightarrow 0$ .*

**Proof.** The idea is to embed  $V$  and  $V'$  into some Hilbert space  $\mathbb{R}^N$  (which is infinite-dimensional if  $V$  and  $V'$  are noncompact) in a rather canonical way, so that their images will be  $C^1$ -close whenever  $V$  and  $V'$  are Hausdorff close. Then we take the normal projection of  $V$  to  $V'$  for the required bi-Lipschitz map  $V \rightarrow V'$ .

Let us explain our construction of the embedding  $\Phi : V \rightarrow \mathbb{R}^N$ . We choose an  $\varepsilon$ -separated  $\varepsilon$ -net in  $V$ , denoted  $\{v_i\} \subset V$ ,  $i = 1, 2, \dots$  and take the space  $\mathbb{R}^N$  of  $\ell_2$ -functions on the set  $\{v_i\}$  so that  $N = \text{card}\{v_i\}$ . Then every  $v \in V$  is sent to the vector  $v \mapsto \{\varphi(\varepsilon^{-1} \text{dist}(v, v_i))\}$ , where  $\varphi$  is some standard smooth function with the following properties

$$\begin{aligned} \varphi(d) &= d^2 && \text{for } d \leq 5 \\ \varphi(d) &= 0 && \text{for } d \geq 6. \end{aligned}$$

Observe that the image of an  $R$ -ball  $B(R) \subset V$  under  $\Phi$  lands in a subspace  $\mathbb{R}^{N_0} \subset \mathbb{R}^N$  with  $N_0 = N_0(n, R)$ . Furthermore, the map  $\Phi|_{B(R)}$  is entirely determined by what happens on the concentric ball  $B(R + 6\varepsilon)$  and so the study of  $\Phi$  is essentially a local matter. We shall be interested in the picture where  $\varepsilon$  is small,  $\varepsilon \ll 1$ , as well as  $\varepsilon \ll \text{InjRad } V$ , and we shall be looking at balls of radius, say  $8\varepsilon$ , where the geometry is essentially Euclidean. So, we look first at our  $\Phi$  in the case of  $V = \mathbb{R}^n$  and observe that this  $\Phi = \Phi^\circ : \mathbb{R}^n \rightarrow \mathbb{R}^\infty$  enjoys the following properties

- (A)  $\Phi^\circ$  is a smooth embedding, i.e., the function  $\varphi_i(v) = \varphi(\text{dist}(v, v_i))$  separates the points in  $\mathbb{R}^n$ , and the differential  $D\Phi^\circ : T(\mathbb{R}^n) \rightarrow \mathbb{R}^\infty$  is everywhere injective.
- (B) The curvature of the embedded  $\Phi^\circ(\mathbb{R}^n) \subset \mathbb{R}^\infty$ , i.e. the norm of the second fundamental form, is bounded by some universal constant  $\text{const} = \text{const}_n$ .

(C)  $\Phi^\circ$  is invariant under the scaling: if we pass from an  $\varepsilon$ -net  $\{v_i\} \subset \mathbb{R}^n$  to the  $\lambda\varepsilon$ -net  $\lambda\{v_i\} \subset \lambda\mathbb{R}^n = \mathbb{R}^n$ , we get the same image in  $\mathbb{R}^\infty$ .

The proof of (A), (B), and (C) is trivial. In fact, one can say more than that. Namely, there is the following (equally obvious) quantitative version of (A):

(A') The metric in  $\mathbb{R}^n$  induced from  $\mathbb{R}^\infty$ , say  $\text{dist}^*$  is comparable to the Euclidean  $\text{dist}$ ,

$$C_1 \text{dist}(v_1, v_2) \leq \text{dist}^*(v_1, v_2) \leq C_2 \text{dist}(v_1, v_2)$$

for all  $v_1$  and  $v_2$  in  $V$  satisfying  $\text{dist}(v_1, v_2) \leq 10\varepsilon$  and for some universal constants  $C_1, C_2$  depending only on  $n$ .

Now, let us compare  $\Phi^\circ$  on  $\mathbb{R}^n$  with  $\Phi$  on an arbitrary  $V$  where  $\varepsilon$  is small compared to  $|K(V)|^{-1}$  and  $\text{InjRad}(V)$ . Since everything is scale invariant, we may assume  $\varepsilon = 1$  while  $|K(V)|^{-1}$  and  $\text{InjRad } V$  are very large, so that the balls, say  $B(7) \subset V$  on which we study  $\Phi$  are close to the Euclidean  $B(7)$  in the Lipschitz metric.

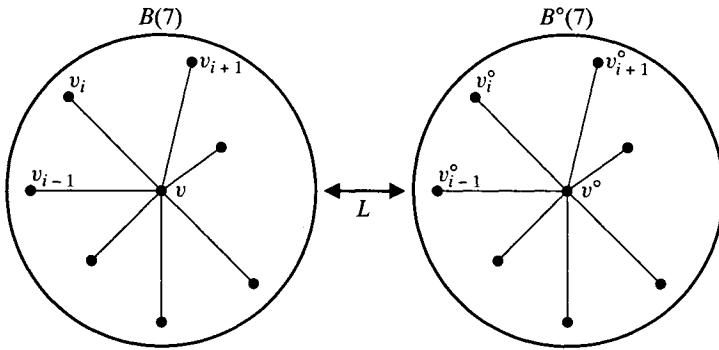
So, we fix such a  $(1 + \Delta_0)$ -bi-Lipschitz diffeomorphism

$$V \supset B(7) \xleftarrow{L} B^\circ(7) \subset \mathbb{R}^n$$

and compare  $\Phi$  on  $B(7) \subset V$  to  $\Phi^\circ$  on  $B^\circ(7) \subset \mathbb{R}^n$ , where the net in  $\mathbb{R}^n$  corresponds to a given net  $\{v_i\} \subset V$  for  $v_i \xrightarrow{L} v_i^\circ$ . We claim that:

*If  $|K(V)| \leq \kappa = \kappa(n) > 0$  and  $\text{InjRad}(V) \geq 20$ , then the map  $\Phi: V \rightarrow \mathbb{R}^n$  satisfies the same properties (A), (B), (C), (A') possibly with different, but still universal, implied constants. Furthermore, the  $\Phi$ -image of  $B(7)$  in  $\mathbb{R}^N$  lies  $C^1$ -close to the  $\Phi^\circ$ -image of  $B^\circ(7)$ , where “close” means  $\Delta$ -close with  $\Delta = \Delta_n(\kappa) \xrightarrow{\kappa \rightarrow 0} 0$  for  $\kappa \rightarrow 0$ .*

**Proof.** Properties (A), (C), and (A') follow from the Rauch theorem, while (B) is immediate with our bounds on the curvatures of spheres in  $V$  by the curvature. The most important feature to grasp is the differential  $D\Phi(v)$  as it compares to  $D\Phi^\circ(v^\circ)$  at the corresponding point  $v^\circ \in \mathbb{R}^n$ . These differentials are determined by the gradients of the corresponding functions  $\varphi(\text{dist}_V(v, v_i))$  and  $\varphi(\text{dist}_{\mathbb{R}^n}(v^\circ, v_i^\circ))$ , and the Rauch theorem applied to  $\exp_v: T_v(V) \rightarrow V$  shows that the metrics in  $V$  and  $\mathbb{R}^n$  induced from  $\mathbb{R}^N$  are mutually close. In fact,  $\Phi$  and  $\Phi^\circ$  distort the original metrics in  $V$  and in  $\mathbb{R}^n$  in the same way, since the gradients of the functions  $\varphi(\text{dist}(v, v_i))$  at  $v$  are directed by the geodesic segments  $[v, v_i]$  with the norm equal to  $|\varphi'(0)|$ .



It follows that the normal projection of  $\Phi(B(7))$  to  $\Phi^\circ(\mathbb{R}^n)$  (as well as of  $\Phi(B^\circ(7))$  to  $\Phi(V)$ ) is an almost isometric map, i.e.  $(1 + \Delta)$ -bi-Lipschitz with  $\Delta \rightarrow 0$  as  $\kappa \rightarrow 0$ .

Now everything is prepared to study two Riemannian manifolds  $V, V'$  which are Hausdorff-close. Here, by the definition of  $d_H$ , we have  $\varepsilon$ -nets  $\{v_i\} \subset V$  and  $\{v'_i\} \subset V'$ , where the correspondence  $v_i \xleftrightarrow{H} v'_i$  is almost isometric, and where the nets can be assumed to be  $\varepsilon$ -separated. So, we have two embeddings  $\Phi : V \rightarrow \mathbb{R}^N$  and  $\Phi' : V' \rightarrow \mathbb{R}^N$  which are both almost parallel to  $\Phi^\circ : \mathbb{R}^n \rightarrow \mathbb{R}^N$  on the balls of radii  $7\varepsilon$  in  $V$  and  $V'$ . It follows that the normal projection  $P$  of  $\Phi(V')$  to  $\Phi(V)$  gives us the desired  $(1 + \Delta)$ -bi-Lipschitz map

$$V' \xrightarrow{\Phi'} \Phi'(V') \xrightarrow{P} \Phi(V) \xrightarrow{\Phi^{-1}} V.$$

As an additional bonus, our (B) gives us a bound on the derivatives of our diffeomorphism  $V' \rightarrow V$  which will come in handy later on.

**Encouraging remark.** All this may appear rather elaborate at first glance with many details needing to be verified. However, once one gets a clear picture of  $\Phi$  for  $V = \mathbb{R}^n$  and accepts that all  $V$ 's are locally very close to  $\mathbb{R}^n$ , as far as the distance functions and their first and second derivatives are concerned (provided, of course, that  $|K(V)|$  is small and  $\text{InjRad } V$  is not very small), then everything becomes obvious up to a point where one cannot even remember what the problem was to begin with.

**8.20.  $C^{1,1}$ -convergence.** The class of manifolds with  $|K(V)| \leq C$  form a Hausdorff precompact family, and the extra condition  $\text{InjRad}_{v_0}(V) \geq \rho_0 > 0$  makes it *Lipschitz precompact*, since the lower bound on the injectivity radius propagates from point to point, as we saw earlier, and then (1) applies. This shows that the Hausdorff limits  $V_\infty$  of manifolds  $V_i$  from our class are Riemannian manifolds and that the convergence  $V_i \rightarrow V_\infty$  is Lipschitz.

Moreover, this limit manifold  $V_\infty$  admits a natural  $C^{1,1}$  structure, where  $C^{1,1}$  refers to  $C^1$  smooth functions with Lipschitz derivatives. Indeed, our  $V_i$ 's were embedded into  $\mathbb{R}^N$  with a *uniform control on the curvature* of the embeddings and uniformly  $C^1$  functions become Lipschitz in the limit.

Thus, we arrive at the class of *Riemannian  $C^{1,1}$  manifolds*  $V$ , which means the following:

- I.  $V$  has a  $C^{1,1}$  atlas with the metric tensor  $g$  of  $V$  being Lipschitz in these  $C^{1,1}$ -coordinates.
- II. The squared distance function  $\text{dist}_g^2$  is *locally*  $C^{1,1}$ .
- III. Every two nearby points in  $V$  are joined by a unique minimal geodesic.
- IV. The exponential map  $\exp_v : T_v(V) \rightarrow V$  is globally defined (if  $V$  is complete) and locally Lipschitz. Moreover, it satisfies Rauch bounds on  $D\exp_v$  corresponding to the inequality  $|K| < C$ .
- V. There exists a bounded, measurable quadratic form  $B_S$  satisfying the definition of the curvature for equidistant deformations of hypersurfaces in  $V$  given in 8.7.

Summing up all of the above, we conclude with the following

**$C^{1,1}$ -compactness theorem:** *The class of the above manifolds  $V$  with the additional requirement  $\text{InjRad}_{v_0}(V) \geq \rho_0 > 0$  is compact in the Lipschitz (as well as Hausdorff) metric for pointed manifolds. Moreover, the implied bi-Lipschitz maps  $L(R)$  from  $R$ -balls  $B_{v_0}(R) \subset V_i$  to  $V_\infty$  can be chosen  $C^{1,1}$  with the bounds on the Lipschitz constants of the differentials  $DL_i(R)$  depending only on  $R$ , for all  $R > 0$ . In particular, if the  $V_i$  are compact with diameters bounded independently of  $i$ , then the  $V_i$  are diffeomorphic to  $V_\infty$  for all sufficiently large  $i$ .*

**Remarks.** (a) This result for *flat tori* is equivalent to the Mahler compactness theorem and the case of locally homogeneous manifolds is due to Chabauty (see [Chab], [Cass], p. 134, and [Che]Fin).

(b) Since  $g$  has a (generalized) bounded curvature and since curvature carries the essential (Diff-invariant) information on the second derivatives of  $g$ , one can expect that  $g$  is  $C^{1,1}$  in suitable coordinates. In fact, it receives a regularity boost if one uses the harmonic coordinates in  $V$ , i.e. those given by harmonic functions (see [Greene] and the references therein).

**8.21. Geometry of  $V$  with  $|K(V)| \leq 1$  on the scale  $\rho_0 = \text{InjRad}_{v_0}(V)$ .** Suppose that we have our  $V$  with small  $\rho_0$  and then scale it by  $\rho_0^{-1}$ . Now

the family  $\{\rho_0^{-1}V_0, v_0\}$  is amenable to the compactness theorem above for  $\rho_0^{-1} \rightarrow \infty$ . Here, if the  $\rho_0^{-1}V$  converge to some  $V_\infty$  for  $\rho_0 \rightarrow 0$ , then the limit manifold  $V_\infty$  is necessarily (and obviously, since  $K(\rho^{-1}(V_i)) = \rho_0^2 K(V) \rightarrow 0$ ) *flat*. Thus, the geometry of each ball  $B_{v_0}(\lambda\rho_0) \subset V$  is close to that of a  $\lambda\rho_0$ -ball in a flat manifold. This applies to all  $\lambda \geq 1$  with the implied closeness depending on  $\lambda$  and becoming “infinitely close” for every fixed  $\lambda$  as  $\rho_0 \rightarrow 0$ . In other words, everything we know about flat manifolds essentially extends to all  $V$  if we are concerned with balls  $B_{v_0}(R)$  with  $R$  comparable to  $\rho_0$ .

**8.22. Pinching without collapse.** We look again at our stability problem (often referred to as “pinching” in the geometric literature). If the manifolds  $V'$  we study, which are infinitesimally (or locally) close to the model  $V_0$ , all have  $|K(V')| \leq C$  and  $\text{InjRad}(V') \geq \rho$ , then, assuming that they also have uniformly bounded diameter, we conclude that they must be close to some development  $V$  of  $V_0$ . Indeed, since we have a sequence of such manifolds  $V_i$  getting locally closer and closer to  $V_0$ , we can take a convergent subsequence and pass to the limit  $V'_\infty$ . This manifold, on the one hand, is locally *isometric* to  $V_0$  as “close” between  $V'_i$  and  $V_0$  becomes “infinitely close” in the limit. On the other hand, the  $V'_i$  are globally close to  $V'_\infty$  by the preceding discussion.

**8.23. Criteria for noncollapse.** It is psychologically easy to include the bound  $|K(V')| \leq C$  into the local closeness of  $V'$  to  $V_0$  condition, since  $V_0$ , being locally homogeneous, has bounded curvature. But the lower bound on  $\text{InjRad}(V')$  is of a global nature and cannot be accepted without some resistance. Fortunately, there are some criteria for this encoded into the local geometry of  $V_0$ , such as nonvanishing of some Chern-Weil form on  $V_0$ . In fact, the most interesting of these is the (generalized) Cheeger criterion, which requires the 2-connectedness of the simply connected development of  $V_0$  (see [Gro]<sub>stab</sub> and the references therein). Notice, however, that even the innocuous looking condition  $|K(V')| \leq \text{const}$  somewhat limits the logical structure of the general stability problem and, in fact, most of the results established (in the present-day literature) for  $|K| \leq C$  extends to the general setting of 8.5. (Some of this is briefly indicated in 8.25 below.)

Besides local criteria, there are global topological ones for noncollapse of metrics on  $V$ . For example, let  $V$  admit a proper map of nonzero degree onto a closed manifold  $V_0$  with negative sectional curvature. Then it cannot collapse if we keep  $|K(V)| \leq \text{const}_1$  and  $\text{diam}(V) \leq \text{const}_2$ , as follows trivially from 5.24, in the case where  $\pi_1(V) = \pi_1(V_0)$ . The general case

(where one needs a trivial generalization of 5.24 to nonuniversal coverings  $\tilde{V} \rightarrow V$ ) is left to the reader.

**8.24. Remarks and references.** (a) Most ideas of this section can be traced to Cheeger's thesis. Actually, our compactness theorem is a restatement (actually known to Cheeger) of *Cheeger's finiteness theorem*, which claims that *there are at most finitely many diffeomorphism classes of Riemannian manifolds  $V$  satisfying*

1.  $\dim V = n$ ,
2.  $|K(V)| \leq \text{const}_1$ ,
3.  $\text{diam}(V) \leq \text{const}_2$ .

Also the essential ideas of pinching and flat approximation on the scale of  $\text{InjRad } V$  are due to Cheeger.

In his original proof, Cheeger (see [Che]<sub>Fin</sub>) was looking at the matching between exponential charts where the Lipschitz constants (of the coordinate transformations) are controlled by the Rauch theorem. In fact, one could forget at this stage about the curvature and just *postulate* bi-Lipschitz closeness of the unit balls in  $V$  to the Euclidean ones. This would still lead to the finiteness and Lipschitz compactness conclusion following Shikata (compare [Shik]). Also, one can handle in this manner the general pinching problem with  $V'$  being Lipschitz-close to  $V_0$  without an extra curvature assumption on  $V'$ .

(b) An efficient use of the second derivatives and/or covariant parallel fields appears in various proofs (Ruh, Grove, Karcher, see [G-K-R]) of the differential sphere theorem, some of which even apply to Hilbert manifolds and show, in particular, that *a sufficiently strongly pinched simply connected Hilbert manifold  $V$  is bi-Lipschitz equivalent to the sphere  $S^\infty$  with the Lipschitz distance between  $V$  and  $S^\infty$  controlled by the pinching*. The same applies to other infinite dimensional model spaces covered by *finitely many* standard ball-shaped domains, e.g., products  $S^\infty \times S^\infty \times S^\infty \times V_0^n$ ,  $n < \infty$ . (See the expository article [Gro]<sub>Stab</sub> for other aspects of pinching.)

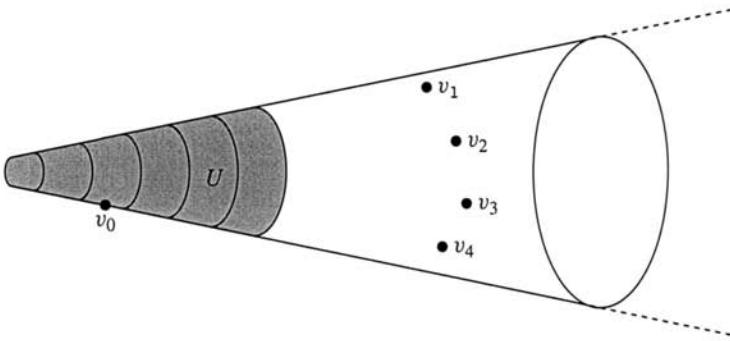
(c) The study of noncollapsed manifolds with  $K(V) \geq -1$  was initiated by Grove and Peterson, and then an essential local geometric property was proven by Perelman.

If  $K(V) \geq -1$  and  $\text{vol } B_{v_0}(1) \geq \varepsilon$ , then the point  $v_0$  admits a convex neighborhood  $U_0 \subset V$  containing the  $\delta$ -ball  $B_{v_0}(\delta)$  for  $\delta \geq \delta_n(\varepsilon) > 0$ ,  $n = \dim V$ .

**Idea of the proof.** Take points  $v_i \in V$ ,  $i = 1, 2, \dots$ , roughly within unit distance from  $v_0$  and consider the functions

$$d_i(v) = (2 - \text{dist}(v_i, v))^N$$

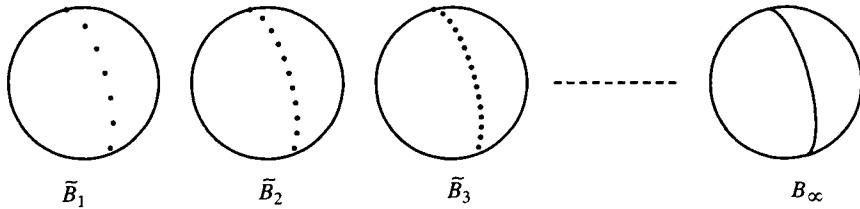
for large  $N$ . Such a function is “strongly convex in many directions” near  $v_0$ , i.e., its second derivative is large and positive along many geodesics. And it is never too concave. (All this follows from the discussion in 8.7.) Then, one can show, (using the lower volume bound  $B_{v_0}(1) \geq \varepsilon$  that the sum  $\sum_i d_i(v)$  for suitably distributed points  $v_i \in V$  is convex and its levels provide enough convex subsets in  $V$  to accomplish what we want (see [Per]SCBB for further results and references).



- (d) The Lipschitz regularity of the Riemannian metric tensor  $g$  on our  $C^{1,1}$  manifolds  $V$  can be upgraded to  $C^{1,\alpha}$ ,  $\alpha > 0$ , by use of *harmonic coordinates* on  $V$ , built of harmonic (instead of distance) functions (see [Sak], [Pugh], [Pet], [Peters], [Katsu], [Gr-Wu], [Greene] and the references therein).

## E. Basic features of collapse

**8.25.** Let us look at the Hausdorff limit  $V_\infty = \lim_{i \rightarrow \infty} V_i$  of a sequence of manifolds  $V_i$  with  $|K(V)| \leq 1$  and  $\text{InjRad } V_i \rightarrow 0$  near some point  $v_\infty \in V_\infty$ . To see what it looks like, we consider the corresponding points  $v_i \in V_i$  converging to  $v_\infty$  and take the exponential unit (multi-)balls  $\tilde{B}_i \rightarrow V_i$  at  $v_i$  with the metrics induced from  $V_i$ . Each  $\tilde{B}_i$  is isometrically acted upon by a discrete pseudogroup  $\Gamma_i$ , and these define in the limit some isometry pseudogroup  $\Gamma_\infty$  on the  $C^{1,1}$ -limit  $\tilde{B}_\infty$  of  $\tilde{B}_i$  (see 8.20). Since the minimal displacement of  $\tilde{v}_i \in \tilde{B}_i$  by  $\Gamma_i$ , i.e.  $2 \text{InjRad}_{v_i}(V_i)$  goes to zero with  $i$ , this limit pseudogroup  $\Gamma_\infty$  is not discrete anymore: it contains a connected normal subpseudogroup  $\Delta_\infty \subset \Gamma_\infty$  acting isometrically on  $\tilde{B}_\infty$ .



It is not hard to see that  $\Delta_\infty$  makes a local Lie group action on  $\tilde{B}_\infty$  (the  $C^{1,1}$ -regularity is enough for this, believe me), and then this local action extends to a global action of a Lie group, say  $\hat{\Delta}_\infty \supset \Delta_\infty$  on some manifold  $\hat{B}_\infty \supset \tilde{B}_\infty$ , such that  $\hat{B}/\Delta_\infty = \tilde{B}_\infty/\Delta_\infty$ .

We add to  $\hat{\Delta}_\infty$  those elements  $\gamma$  in  $\Gamma$  which fix  $\tilde{v}_\infty$  and thus send the orbit  $\hat{\Delta}_\infty(\tilde{v}_\infty)$  into itself and denote the resulting group (not just pseudogroup!) by  $\hat{\Gamma}_\infty \supset \hat{\Delta}_\infty$ . The rest of  $\Gamma_\infty$  acts freely on  $\tilde{B}_\infty$ , and so we see that  $V_\infty$  is locally isometric at  $v_\infty$  to  $\tilde{B}_\infty/\hat{\Gamma}_\infty$ . This gives a fair idea of the local geometry of  $V_\infty$ .

**8.26.** The description above does not tell much about the geometry of the  $V_i$  themselves and/or about  $\Gamma_i$  acting on  $\tilde{B}_i$ . For example, it remains unclear at this stage if the action of the pseudogroup  $\Gamma_i$  comes from a group  $\hat{\Gamma}_i$  acting on some  $\hat{B}_i \supset \tilde{B}_i$ . The first case one may try to look at is where  $\text{diam}(V_i) \rightarrow 0$ , and so the  $V_i$  converge to a single point where the description above is totally vacuous. The manifolds  $V$  where  $|K(V)| \leq 1$  and the diameters are very small are called *almost flat*. Obviously *flat* Riemannian manifolds are almost flat. Furthermore, if  $V' \rightarrow V$  is a circle bundle over an almost flat manifold  $V$ , then  $V'$  is also almost flat by a Berger-like consideration (see 3.11), and one can even allow more general fibers which are flat Riemannian manifolds insofar as the structure group of the fibration is isometric on the fibers. Actually, one can prove that this covers all almost flat possibilities, but one gains in perspective by switching the point of view and identifying the above manifolds with *infranil manifolds*. (The idea of relating almost flatness with nilmanifolds was suggested to me by G. Margulis about 25 years ago.) Actually, a suitable version of the *Margulis lemma* says that the pseudogroup  $\Gamma_i$  acting on  $\tilde{B}_i$  is virtually nilpotent (compare [Zassen]). Then one can show that it does extend to an action of a virtually nilpotent group  $\hat{\Gamma}_i \supset \Gamma_i$  on some  $\hat{B}_i$  (see [Bus–Kar]). Eventually, one can go deeper into the geometry of this action and then analyze how these fit together on different (multi-)balls in  $V_i$ , thus getting a pretty good picture of the local geometry of the collapsed manifolds  $V$  in terms of the so-called *N-structure* (see [Che–Fu–Gr] and the references therein). As an upshot of this, one can prove the existence of the *critical radius*, i.e.,

a number  $\rho = \rho_n > 0$  such that the metric  $g$  on a manifold  $(V, g)$  with  $|K| \leq 1$  and  $\text{InjRad}_v \leq \rho$  for all  $v \in V$  admits a deformation  $g_t$  so that  $\text{InjRad}_v(V, g_t) \xrightarrow{t \rightarrow \infty} 0$  with the curvature remaining bounded by 1. On the other hand, one does not know if there is a similar critical value for the volume (see [Che–Rong], [Fang–Rong], [Pet–Tus], and [Pet–Rong–Tus] in this regard).

We conclude by noting that the structure of collapse has also been studied for manifolds with  $K \geq -1$  and with  $\text{Ricci} \geq -1$ . For example, Perelman (see [Per]\_Wid, [Col]\_ARC, [Grom] and the references therein) proved that collapsed manifolds with  $K \geq -1$  look (very) roughly like convex subsets in  $\mathbb{R}^n$  or like solids  $[0, \varepsilon_1] \times [0, \varepsilon_2] \times \cdots \times [0, \varepsilon_n]$  for some  $\varepsilon_1 \geq \varepsilon_2 \geq \cdots \geq \varepsilon_n$ . Namely, he has shown that, say for  $K \geq 0$ , the volume of  $V$  is commensurable to the product of Uryson diameters (widths)

$$C_1 \prod_{i=0}^{n-1} \text{diam}_i(V) \leq \text{vol } V \leq C_2 \prod_{i=1}^{n-1} \text{diam}_i V$$

for some positive constants  $C_1$  and  $C_2$  depending on  $n$ .

The most challenging open problem is to work out the concept of collapse for manifolds with scalar curvature bounded from below by a constant  $C$ , at least in the case  $C > 0$ .

# Appendix A

## “Quasiconvex” Domains in $\mathbb{R}^n$

by P. Pansu

**A.1. Definition:** A subset  $X$  in  $\mathbb{R}^n$  is called *C-quasiconvex* if, for all points  $x, y \in X$ , there is an arc joining  $x$  to  $y$  in  $X$  having length at most  $C\|x - y\|$ .

**A.2. Remark:** In 1.14, we saw that 1-quasiconvex subsets are actually convex, and that a  $\pi/2$ -quasiconvex set is necessarily simply connected.

On the regular polyhedron with  $n + 1$  vertices, inscribed in the unit sphere in  $\mathbb{R}^n$ , consider two contiguous vertices  $a, b$ . Let  $\alpha$  denote their distance apart with respect to the metric on the sphere:  $\alpha$  is the angle between the vectors  $a$  and  $b$ , and is given by the condition  $\cos(\alpha) = -1/n$ . Let  $\tau$  denote the ratio of the angle  $\alpha$  and the length of the edge  $ab$ , i.e.,  $\tau = \alpha/2 \sin(\alpha/2)$ .

**A.3. Proposition:** *Let  $X$  be a compact,  $C$ -quasiconvex subset of  $\mathbb{R}^n$  with  $C < \tau$ . Consider  $\mathbb{R}^n$  as the complement of a point in  $S^n$ . If  $X$  is precisely the support of a positive finite measure, then  $S^n \setminus X$  is diffeomorphic to a ball.*

The proof consists of an application of Morse theory to a smooth version of the distance function from  $X$ . Given a finite measure  $\mu$  whose support equals  $X$ , we construct a smooth, convex, and decreasing function  $f: \mathbb{R}_+^* \rightarrow$

$\mathbb{R}_+^*$  such that the integral  $D(x) = \int f(\|x - z\|) d\mu(z)$  is finite for precisely those points  $x$  not belonging to  $X$ . The condition of quasiconvexity ensures that the smooth function  $D$  on  $\mathbb{R}^n \setminus X$  has no critical points.

**A.4. Lemma:** *For each positive, finite measure  $\mu$  on  $\mathbb{R}^n$  whose support equals  $X$ , and for each  $r > 0$ , the number  $s(r) = \sup\{\mu(X)/\mu(B(x, r)) : x \in X\}$  is finite.*

Recall that the support of a positive measure is defined by the condition that  $\mathbb{R}^n \setminus \text{Supp}(\mu)$  is the union of all open subsets of  $\mathbb{R}^n$  having zero measure.

Fix a positive measure  $\mu$  whose support equals  $X$ . Then for each  $r > 0$  and  $x \in X$ , we have  $\mu(B(x, r)) > 0$ . Now observe that, in fact,  $\mu(B(x, r)) \geq \varepsilon(r) > 0$  for  $x \in X$ ,  $r > 0$ . Otherwise, there would exist a sequence  $x_i \in X$  such that  $\mu B(x_i, r) \rightarrow 0$ . By passing to a subsequence, we may assume that the  $x_i$  converge to  $x \in X$  and that  $\mu(B(x_i, r)) \leq 2^{-i}$  for each  $i$ . Then

$$B(x, r) \subset \bigcap_{m \geq 0} \bigcup_{i=m}^{\infty} B(x_i, r),$$

and so for each  $m$ ,

$$\mu(B(x, r)) \leq \sum_{i=m}^{\infty} \mu(B(x_i, r)) \leq 2^{-m+1},$$

and finally,  $\mu(B(x, r)) = 0$ , which is impossible.

**A.5. Lemma:** *For each  $a > 0$  and  $\lambda > 1$ , there exists a smooth, strictly decreasing function  $f : (0, a] \rightarrow \mathbb{R}_+$  which bounds  $s$  from above and whose derivative  $f'$  is increasing and satisfies  $-f'(r) \geq 2\sqrt{n}s((\lambda - 1)r)(-f'(\lambda r))$  for  $r \leq a/\lambda$ .*

**Proof.** We first construct a continuous, piecewise affine function  $s_1$  having the desired properties:  $s_1$  is affine on each interval  $[\lambda^{-k-1}a, \lambda^{-k}a]$ , of slope  $p_k$ . We set  $s_1(a) = s(a/\lambda)$  and  $p_1 = (\lambda/(\lambda-1)a)(s(\lambda^{-1}a) - s(\lambda^{-2}a))$ . Then we inductively define  $p_k$  by setting

$$p_k = \sup \left\{ \frac{-p_{k-1}, -p_{k-1}2\sqrt{n}\lambda s((\lambda - 1)\lambda^{-k}a)}{-(\lambda^{k+1}/(\lambda - 1)a)(s(\lambda^{-k-1}a) - s(\lambda^{-k}a))} \right\}.$$

By construction,  $p_k < 0$ , so  $s_1$  is decreasing  $p_k \leq p_{k-1}$ ,  $s'_1$  is increasing, and  $s_1(\lambda^{-k}a) \geq s(\lambda^{-k-1}a)$ ; thus for each  $r \in [\lambda^{-k-1}a, \lambda^{-k}a]$ ,

$$s_1(r) \geq s_1(\lambda^{-k}a) \geq s(\lambda^{-k-1}a) \geq s(r);$$

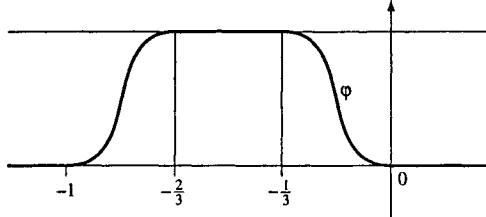
finally, for  $r \in (\lambda^{-k-1}a, \lambda^{-k}a]$  we have

$$\begin{aligned}-s'_1(r) &= -p_k \geq -p_{k-1} 2\sqrt{n}\lambda s((\lambda-1)\lambda^{-k}a) \\ &\geq (-s'_1(\lambda r)) 2\sqrt{n}\lambda s((\lambda-1)r).\end{aligned}$$

It remains only to perform a convolution

$$f(r) = 3 \int s_1(r+t)\varphi(2t/r) dt,$$

where  $\varphi$  is smooth, equals 1 on  $[-2/3, -1/3]$ , and vanishes outside of  $(-1, 0)$ .



Then  $f$  is smooth, and

$$f(r) \geq s_1(r) \geq s(r);$$

like  $s'_1$ , the derivative  $f'$  of  $f$  is negative and increasing, and we have

$$\begin{aligned}-f'(r) &= 3 \int s'_1(r+t)\varphi(2t/r) dt \\ &\geq 6\sqrt{n}\lambda \int -s'_1(\lambda r + \lambda t)s((\lambda-1)(r+t))\varphi(2t/r) dt \\ &= 6\sqrt{n} \int_{-\lambda r/2}^0 -s'_1(\lambda r + t)s((\lambda-1)(r+t/\lambda))\varphi(2t/\lambda r) dt \\ &\geq 6\sqrt{n}s(\lambda-1)r \int -s'_1(\lambda r + t)\varphi(2t/\lambda r) dt \\ &= 2\sqrt{n}s((\lambda-1)r)(-f'(\lambda r))\end{aligned}$$

since  $t \leq 0 \Rightarrow s((\lambda-1)(r+t/\lambda)) \geq s((\lambda-1)r)$ .

In the following, we set  $a = \text{diam}(X)(\lambda/\lambda-1)$ , and we extend  $f$  to a smooth, strictly decreasing function on  $\mathbb{R}_+^*$ .

**A.6. Lemma:** *The function  $D(x) = \int f(\|z-x\|) d\mu(Z)$  is finite precisely on  $\mathbb{R}^n \setminus X$ .*

**Proof.** By hypothesis,  $\mu$  is finite, and if  $x \notin X$ , the function  $z \mapsto f(\|z-x\|)$  is bounded above by  $f(d(x, X)) < \infty$ ; thus,  $D(x)$  is finite. Conversely, if

$x \in X$ , then for each  $r$  such that  $0 < r < a$ ,

$$\begin{aligned} D(x) &\geq \int_{B(x,r)} s(\|z - x\|) d\mu(z) \\ &\geq \int_{B(x,r)} s(r) d\mu(z) \\ &= s(r)\mu(B(x,r)) \\ &\geq \mu(X), \end{aligned}$$

and so the integral cannot be finite.

**A.7. Lemma:** Suppose, moreover, that  $X$  is  $C$ -quasiconvex, with  $C < \tau$ . There exists a  $\lambda > 1$  such that for each  $x \in \mathbb{R}^n \setminus X$ , the distance from  $x$  to the convex hull of  $X \cap B(x, \lambda d(x, X))$  is at least

$$\left( \frac{1}{n} + \lambda^2 \left( \frac{1}{n^2} - \frac{1}{n} \right) \right)^{1/2} d(x, X).$$

**Proof.** Fix  $x \in \mathbb{R}^n \setminus X$ . We will first show that if  $\lambda$  is sufficiently close to 1, then  $x$  is not in the convex hull of  $X \cap B(x, \lambda d)$ , where  $d = d(x, X)$ . If it were, then we could write

$$\sum_{i=0}^n t_i(z_i - x) = 0,$$

where  $t_i \geq 0$ ,  $\sum_i t_i = 1$ , and  $z_i \in X$ ,  $\|z_i - x\| \in [d, \lambda d]$ . Then, for each  $j$ ,  $\sum_{i=0}^n t_i \langle z_i - x, z_j - x \rangle = 0$ , or in other words,  $\sum_{i \neq j} t_i \langle z_i - x, z_j - x \rangle / t_j \|z_j - x\|^2 = -1$ . Let  $j$  be the index for which the number  $t_j \|z_j - x\|$  is largest. Then there exists an  $i \neq j$  such that  $t_i \langle z_i - x, z_j - x \rangle / t_j \|z_j - x\|^2 \leq (1/n)$ , and so the cosine of the angle  $\beta$  between  $z_i - x$  and  $z_j - x$  is at most equal to  $-(1/n)$ . Every path connecting  $z_i$  to  $z_j$  in  $X$  has length at most  $\beta d$ , so that  $\|z_j - z_i\|$  is at most  $2\lambda d \sin(\beta/2)$ . The condition of  $C$ -quasiconvexity implies that  $\beta/2\lambda \sin(\beta/2) \leq C < \alpha/2 \sin(\alpha/2)$  so that, since  $\beta \geq \alpha$ ,  $\lambda \geq C2 \sin(\alpha/2)/\alpha$ . If we fix  $\lambda < C2 \sin(\alpha/2)/\alpha$  so that, for each  $x \in X$ ,  $x$  is distinct from its orthogonal projection  $x'$  onto the convex hull of  $X \cap B(X, \lambda d)$ . In particular,  $x'$  lies on the boundary of the convex hull, so that we can write

$$x' = \sum_{i=1}^n t_i z_i \quad \text{with} \quad \sum_{i=1}^n t_i = 1.$$

Knowing that for each  $i, j$  we have  $\langle z_i - x, z_j - x \rangle / \|z_i - x\| \|z_j - x\| \geq -(1/n)$ , we can compute

$$\begin{aligned}\|x' - x\| &= \sum_{i=1}^n t_i^2 \|z_i - x\|^2 + \sum_{i \neq j} t_i t_j \langle z_i - x, z_j - x \rangle \\ &\geq \sum_{i=1}^n t_i^2 d^2 + \sum_{i \neq j} t_i t_j \left( \frac{1}{n} \lambda^2 d^2 \right) \\ &= d^2 \left[ \left( \sum_{i=1}^n t_i^2 \right) \left( 1 + \frac{1}{n} \lambda^2 \right) - \frac{1}{n} \left( \sum_{i=1}^n t_i \right)^2 \lambda^2 \right] \\ &\geq \frac{1}{n} + \lambda^2 \left( \frac{1}{n^2} - \frac{1}{n} \right) d^2,\end{aligned}$$

since the function  $(t_1, \dots, t_n) \mapsto t_1^2 + \dots + t_n^2$  attains its minimum at the point  $t_1 = \dots = t_n = 1/n$ .

**A.8. Lemma:** *If  $X$  is  $C$ -quasiconvex, with  $C < \tau$ , then the function  $D$  of Lemma A.6 is smooth and has no critical points on  $\mathbb{R}^n \setminus X$ .*

**Proof.** Since the measure  $\mu$  is finite and since the functions  $z \mapsto f(\|z - x\|)$  and  $z \mapsto (d^p/dz^p)f(\|z - x\|)$  are uniformly bounded in a neighborhood of each point of  $\mathbb{R}^n \setminus X$ , the function  $D$  is of class  $C^\infty$ . The gradient of  $D$  at a point  $x \in X$  is  $\text{grad}_x D = \int (f'(\|z - x\|)/\|z - x\|)(x - z) d\mu(z)$ . Set  $d = d(x, X)$  and fix a  $\lambda$  satisfying the condition of Lemma A.7. The point

$$g = x + \frac{1}{I} \int_{B(x, \lambda d)} \frac{f'(\|z - x\|)}{\|z - x\|} (x - z) d\mu(z),$$

where

$$I = \int_{B(x, \lambda d)} -\frac{f'(\|z - x\|)}{\|z - x\|} d\mu(z)$$

is the center of mass of  $X \cap B(x, \lambda d)$  equipped with the density  $(-f'(\|z - x\|)/\|z - x\|)\mu$ , and is therefore contained in the convex hull of  $X \cap B(x, \lambda d)$ , so that by Lemma A.7

$$\|x - g\| \geq \left( \frac{1}{n} + \lambda^2 \left( \frac{1}{n^2} - \frac{1}{n} \right) \right)^{1/2} d.$$

On the other hand,  $(1/I) \text{grad}_x D - (x - g)$  equals the remainder of the integral, so that

$$\begin{aligned}\left\| \int_{\mathbb{R}^n \setminus B(x, \lambda d)} \frac{f'(\|z - x\|)}{\|z - x\|} (x - z) d\mu(z) \right\| &\leq \int_{\mathbb{R}^n \setminus B} -f'(\lambda d) d\mu(z) \\ &\leq -\mu(X) f'(\lambda d),\end{aligned}$$

so that

$$I = \int_{B(x, \lambda d)} -\frac{f'(\|z - x\|)}{\|z - x\|} d\mu(z) \geq -\frac{f'(d)}{d} \mu(B(x, \lambda d)),$$

and we obtain

$$\left\| \frac{1}{I} \operatorname{grad}_x D - (x - g) \right\| \leq d\mu(X) \frac{f'(\lambda d)}{f'(d)} \mu(B(x, \lambda d)).$$

However, there exists a  $z \in X$  such that  $\|z - x\| = d$ . Thus  $B(z, (\lambda - 1)d) \subset B(x, \lambda d)$ , so that  $\mu(X)/\mu(B(x, \lambda d)) \leq \mu(X)/\mu(B(z, (\lambda - 1)d)) \leq s((\lambda - 1)d)$ , which gives the inequality  $\|(1/I) \operatorname{grad}_x D - (x - g)\| < \|x - g\|$  for  $d \leq a/\lambda = \operatorname{diam}(X)/\lambda - 1$ , and  $\lambda$  sufficiently close to 1. For  $d > \operatorname{diam}(X)/\lambda - 1$ ,  $X \subset B(x, \lambda d)$ , so  $(1/I) \operatorname{grad}_x D = x - g$ . In both cases, we conclude that  $\operatorname{grad}_x D \neq 0$ .

**A.8. Proof of the Proposition:** The function  $f$  was constructed explicitly on  $[0, a]$ , but until now we have only used the fact that on  $[a, \infty)$ ,  $f$  is smooth and strictly decreasing. We can therefore assume that for sufficiently large  $r$ ,  $f(r) = 1/r^2$ . Then  $D$  tends to 0 at infinity. To verify that the natural extension of  $D$  to  $S^n$  is smooth, it suffices to compose  $D$  with the inversion  $x \mapsto x/\|x\|^2$ , which is a chart from  $\mathbb{R}^n$  onto  $S^n \setminus \{0\}$ . We may assume that 0 is the center of mass of  $X$  with respect to the measure  $\mu$ , in which case it is easy to check that if  $D_0$  is the function  $D$  associated with the set  $\{0\}$  equipped with the Dirac measure  $\mu(\{0\})$ , then

$$D\left(\frac{X}{\|X\|^2}\right) = D_0\left(\frac{X}{\|X\|^2}\right) + O(\|X\|^3),$$

which proves that  $D$  is thrice-differentiable at 0, and has the same derivative and hessian as  $D_0$ . But  $D_0(X/\|X\|) = \|X\|^2$ , and so  $D_0$  (and  $D$ ) admit a nondegenerate critical point at  $\infty$  having index  $n$ . Morse theory (cf. [Milnor]MT) then enables us to conclude that  $S^n \setminus X$  is diffeomorphic to a ball.

**Remark:** We can construct the diffeomorphism  $\varphi : B^n \rightarrow S^n \setminus x$  in an equivariant way, i.e., there exists a homomorphism  $h : \operatorname{Isom}(X) \rightarrow \operatorname{Isom}(B^n)$  such that for each isometry  $i$  fixing  $X$ , we have  $i \circ \varphi = \varphi \circ h(i)$ . Indeed, the compact Lie group  $\operatorname{Isom}(X)$  admits a fixed point  $\mu$  in the compact, convex set of measures  $\mu$  of support  $X$ , mass 1, such that

$$\mu = \int_{\operatorname{Isom}(X)} g^* \mu_0 dg$$

for a Haar measure  $dg$  on  $\operatorname{Isom}(X)$ .

**A.9. Corollary:** *Under the hypotheses of the proposition, and if  $X$  is also an absolute neighborhood retract having the homotopy type of a CW complex, then  $X$  is contractible.*

Indeed, it follows from Alexander duality (see [Span], Ch. 7) that  $X$  has trivial cohomology and is thus contractible.

## Appendix B

# Metric Spaces and Mappings Seen at Many Scales

by Stephen Semmes

This appendix describes some geometric ideas from classical analysis and quasiconformal mappings. We shall study spaces and mappings at all locations and scales at once. Every ball in a metric space provides a snapshot, of the space itself or a mapping on it. We shall often consider situations in which these snapshots are “bounded”. We shall encounter a variety of forms of boundedness of snapshots. A bound on a single snapshot is not so exciting, but uniform bounds on all snapshots can lead to interesting structure.

An important point is to use measure theory. With measure theory we can see interesting phenomena which happen “most of the time”. We shall sometimes see hidden rigidities, in which there is special structure that does not occur in all contexts and which is not explicit in the definitions.

In Part I we review some definitions, making precise the idea of bounded snapshots in various ways. We shall also review examples of metric spaces and a few basic facts to show how the concepts fit together. In Part II we go through some machinery for working with spaces and functions which have bounds on their snapshots. The results discussed there work in great

generality and are not very mysterious. In Part III we concentrate on more mysterious phenomena that involve special structure and hidden rigidities. Part IV provides an introduction to real variable methods that support much of the material in Part III and which deal with the interplay between measure theory and the geometry of snapshots.

## I. Basic concepts and examples

### B.1. Euclidean spaces, hyperbolic spaces, and ideas from analysis.

Euclidean spaces and hyperbolic spaces are basic examples of metric spaces that one thinks of as being very different. They *are* very different, but they can also be seen as different ways to look at the same thing.

Euclidean space means  $\mathbb{R}^n$  with the usual metric  $|x - y|$ . For hyperbolic space we use the upper half-space model. Set  $\mathbb{R}_+^{n+1} = \{x = (x_1, \dots, x_{n+1}) \in \mathbb{R}^{n+1} : x_{n+1} > 0\}$ . The hyperbolic Riemannian metric on  $\mathbb{R}_+^{n+1}$  is defined by

$$\frac{dx_1^2 + \cdots + dx_{n+1}^2}{x_{n+1}^2}. \quad (\text{B.1.1})$$

Let  $h(x, y)$  be the geodesic distance function on  $\mathbb{R}_+^{n+1}$  associated to this Riemannian metric, so that  $h(x, y)$  is the length with respect to (1.1) of the shortest curve in  $\mathbb{R}_+^{n+1}$  which connects  $x$  to  $y$ . One can write down an explicit formula for  $h(x, y)$ , but I think that it is easier to understand some cruder considerations. Fix a point  $x \in \mathbb{R}_+^{n+1}$ . If  $y \in \mathbb{R}_+^{n+1}$  satisfies

$$|x - y| \leq \frac{x_{n+1}}{2}, \quad (\text{B.1.2})$$

so that  $y$  is substantially closer to  $x$  than to the boundary hyperplane  $\mathbb{R}^n \times \{0\}$ , then  $h(x, y)$  is bounded by a universal constant. Thus if you start at  $x$  and move a distance at most  $x_{n+1}/2$  in the Euclidean metric, then you move only a bounded distance in the hyperbolic metric. More generally, if

$$|x - y| \leq k x_{n+1} \quad \text{and} \quad k^{-1} x_{n+1} \leq y_{n+1} \leq k x_{n+1} \quad (\text{B.1.3})$$

for some constant  $k > 0$ , then  $h(x, y) \leq C(k)$  for some constant  $C(k)$  that does not depend on  $x$  or  $y$ . Conversely, if  $h(x, y) \leq A$  for some constant  $A$ ,

then (1.3) holds for some constant  $k$  that depends only on  $A$  and not on  $x$  or  $y$ .

So how is it that hyperbolic spaces and Euclidean spaces describe the same thing?

Think of  $\mathbb{R}_+^{n+1}$  as parameterizing all the balls in  $\mathbb{R}^n$ . That is, if  $x \in \mathbb{R}_+^{n+1}$ , then we set  $x' = (x_1, \dots, x_n)$ , we get a ball  $B(x) = B(x', x_{n+1})$  in  $\mathbb{R}^n$ , and all balls arise this way. If we view  $\mathbb{R}_+^{n+1}$  as the space of balls in  $\mathbb{R}^n$ , then the coarse geometry described above is very natural. To say that  $x, y \in \mathbb{R}_+^{n+1}$  have bounded hyperbolic distance  $h(x, y)$  means that the balls  $B(x)$  and  $B(y)$  are pretty similar, i.e., they have approximately the same radius (to within a bounded factor), and the distances between the centers is bounded by a constant times the radius.

We can think of this relationship between Euclidean space  $\mathbb{R}^n$  and hyperbolic space  $\mathbb{R}_+^{n+1}$  in the following way. Think of  $\mathbb{R}^n$  as being the place where we live, like the surface of the Earth, and think of  $\mathbb{R}_+^{n+1}$  as being the sky above. We might be able to fly around in  $\mathbb{R}_+^{n+1}$  like an insect or a bird or a helicopter and look down on  $\mathbb{R}^n$  below. If we are at the point  $x \in \mathbb{R}_+^{n+1}$ , then the ball  $B(x)$  is roughly the part of  $\mathbb{R}^n$  that we can see best. We cannot see things in  $B(x)$  too clearly, we cannot make distinctions that exist at distances much smaller than  $x_{n+1}$ . Our vision is limited both by location and scale. If we need to see something more precisely we have to fly down closer to the ground. If we want a broad perspective, then we have to fly high.

This idea plays a very important role in analysis. Suppose that  $n = 1$ , so that we can think of  $\mathbb{R}_+^2$  as being the upper half-plane in the complex plane. Suppose that  $f(z)$  is a bounded holomorphic function on  $\mathbb{R}_+^2$ . It turns out that the gradient of  $f$  is automatically bounded in the hyperbolic metric. In other words  $f$  has to be almost constant on small hyperbolic balls. This can be checked using the Cauchy integral formula. If we think of  $f$  as being represented as the Cauchy integral of its boundary values on the real axis – i.e.,

$$f(z) = \frac{1}{2\pi i} \int_{\mathbb{R}} \frac{f(t)}{t - z} dz \quad (\text{B.1.4})$$

for  $z \in \mathbb{R}_+^2$  – then the value  $f(z)$  is most sensitive to the boundary values  $f(t)$  for  $t \in B(z)$ , because the Cauchy kernel  $\frac{1}{t-z}$  is largest for  $t \in B(z)$  and decays as  $t$  moves away from  $B(z)$ . (This works better if one uses the Poisson integral formula.)

These comments are not special to holomorphic functions of one complex variable. They apply to harmonic functions, and in higher dimensions. They should be seen in the context of elliptic partial differential equations.

There are versions for holomorphic functions of several complex variables, although the correct geometry is different.

Similar ideas arise in analysis in other ways. One often studies functions on  $\mathbb{R}^n$  by looking at their average behavior on balls, looking at different centers and radii. This includes the average oscillations of a function on balls. In this way one often starts with a function on  $\mathbb{R}^n$  and then passes to an associated function on  $\mathbb{R}_+^{n+1}$  which captures some aspect of the behavior of the original function on average, at different scales and locations. For instance, given a locally integrable function  $g(u)$  on  $\mathbb{R}^n$ , one might consider the functions  $G(x)$ ,  $H(x)$  on  $\mathbb{R}_+^{n+1}$  defined by

$$G(x) = \frac{1}{|B(x)|} \int_{B(x)} g(u) du, \quad (\text{B.1.5})$$

$$H(x) = G(x) - G(\hat{x}), \quad \hat{x} = (x_1, \dots, x_n, 2|x_{n+1}|). \quad (\text{B.1.6})$$

Here  $|B(x)|$  the volume of the ball  $B(x)$ , so that  $G(x)$  is just the average of  $g$  over  $B(x)$ , and  $H(x)$  is the difference between the average of  $g$  over  $B(x)$  and its double (the ball with the same center but twice the radius). One can think of  $H(x)$  as measuring the oscillation of  $g$  near  $B(x)$ , so that  $H(x)$  is small when  $g$  is almost constant on the double of  $B(x)$ . (This will happen when  $g$  is continuous and  $B(x)$  is small, i.e.,  $x_{n+1}$  is small.) The behavior of both  $G(x)$  and  $H(x)$  are approximately compatible with hyperbolic geometry on  $\mathbb{R}_+^{n+1}$ , e.g., we do not expect them to oscillate very much on small hyperbolic balls. If  $g(u)$  is bounded, for instance, then  $G(x)$  and  $H(x)$  are Lipschitz functions with respect to the hyperbolic metric, so that the amount by which their values change when we move  $x$  is bounded by a constant times the hyperbolic distance between  $x$  and the new point.

## B.2. Quasimetrics, the doubling condition, and examples of metric spaces.

For the record, a metric on a (nonempty) set  $M$  is a nonnegative function  $d(x, y)$  on  $M \times M$  which is symmetric, vanishes exactly when  $x = y$ , and satisfies the triangle inequality. We call  $d(x, y)$  a quasimetric if it satisfies the same properties except that the triangle inequality is replaced by

$$d(x, z) \leq K(d(x, y) + d(y, z)) \quad (\text{B.2.1})$$

for some constant  $K > 0$  and all  $x, y, z \in M$ .

The diameter of a set  $E \subseteq M$  with respect to  $d(x, y)$  is given by  $\text{diam } E = \sup\{d(x, y) : x, y \in E\}$ . We write  $B(x, r)$  and  $\overline{B}(x, r)$  for the open and closed balls with center  $x$  and radius  $r$ .

If  $d(x, y)$  is a quasimetric on  $M$ , then there exists a metric  $\rho(x, y)$  on  $M$  and constants  $C > 0$  and  $s \geq 1$  so that

$$C^{-1} \rho(x, y)^s \leq d(x, y) \leq C \rho(x, y)^s \quad (\text{B.2.2})$$

for all  $x, y \in M$ . This is essentially the content of the proof of Theorem 2 in [Mac–Sego].

**B.2.3. Definition:** A metric space  $M$  is said to be doubling if there is a constant  $C$  so that any ball  $B$  in  $M$  can be covered with at most  $C$  balls whose radius is half the radius of  $B$ .

This is a kind of uniform finite-dimensionality condition. It is satisfied by Euclidean spaces and it is not satisfied by hyperbolic spaces. For hyperbolic spaces one has the doubling property for balls of bounded radius but not for large balls. If we think of hyperbolic spaces and Euclidean spaces as corresponding in the manner of Section 1, then the doubling property for all balls for Euclidean spaces is connected to the doubling property for balls of bounded radius for hyperbolic spaces.

The doubling property provides a way to say that all snapshots of a metric space are bounded.

**B.2.4. Lemma:** A metric space  $M$  is doubling if and only if every ball  $B$  in  $M$  can be covered by a bounded number of subsets of  $M$  with diameter at most half the radius of  $B$ .

This is easy to check.

**B.2.5. Corollary:** If the metric space  $M$  is doubling, then so is any subspace of  $M$ .

In particular any subset of a Euclidean space is doubling.

**B.2.6. Definition:** Let  $(M, d(x, y))$  and  $(N, \rho(u, v))$  be metric spaces and let  $f : M \rightarrow N$  be a mapping between them. We say that  $f$  is  $C$ -Lipschitz if

$$\rho(f(x), f(y)) \leq C d(x, y)$$

for all  $x, y \in M$ , and we say that  $f$  is  $C$ -bi-Lipschitz if

$$C^{-1} d(x, y) \leq \rho(f(x), f(y)) \leq C d(x, y) \quad (\text{B.2.7})$$

for all  $x, y \in M$ . We shall just say Lipschitz or bi-Lipschitz if we do not need to specify the constant. We say that two metric spaces are bi-Lipschitz equivalent if there is a bi-Lipschitz mapping from one onto the other.

Note that compositions of Lipschitz mappings are Lipschitz, and similarly for bi-Lipschitz mappings.

The Lipschitz and bi-Lipschitz conditions can be seen as ways to bound the snapshots of a given mapping.

We need to start collecting some examples of metric spaces. Let us begin with a general operation called the *snowflake functor*. If  $(M, d(x, y))$  is a metric space and  $0 < s < 1$ , then we can get a new metric space by replacing  $d(x, y)$  with  $d(x, y)^s$ . This is indeed a metric, because of the well-known fact that

$$(a + b)^s \leq a^s + b^s \quad (\text{B.2.8})$$

when  $a, b$  are nonnegative real numbers and  $0 < s < 1$ . When  $s > 1$  we do not get a metric but we do get a quasimetric.

This operation is called the snowflake functor because it is an abstract version of the familiar constructions of snowflake curves in the plane. Indeed the standard snowflake constructions give curves which are bi-Lipschitz equivalent to the snowflake functor applied to a circle or line segment (with a suitable choice of  $s$ ). [The most famous snowflake curve is the Von Koch snowflake, which is obtained in the following manner. One starts with an equilateral triangle  $T_0$  in the plane, viewed as a simple closed curve. One then replaces the middle third of each of the three sides of  $T_0$  with a pair of segments of the same length which point outside  $T_0$ , so as to make a simple closed curve  $T_1$  which is the union of twelve segments of equal length. One then repeats the construction to produce Jordan curves  $T_2, T_3, \dots$ , with each  $T_j$  consisting of  $3 \cdot 4^j$  segments of length  $3^{-j}$  times the length of the sides of  $T_0$ . The Von Koch snowflake is obtained as the limit of the  $T_j$ 's (in the Hausdorff topology for compact sets).]

Note that  $(M, d(x, y))$  is doubling if and only if  $(M, d(x, y)^s)$  is doubling.

As a variation on the theme of snowflakes consider  $\mathbb{R}^{n+1}$  with the metric defined by

$$d(x, y) = |x' - y'| + |x_{n+1} - y_{n+1}|^{\frac{1}{2}}, \quad (\text{B.2.9})$$

where  $x'$  denotes the point  $(x_1, \dots, x_n)$  of  $x$  in  $\mathbb{R}^n$ . This space is doubling. It defines the natural geometry on  $\mathbb{R}^{n+1}$  for studying the heat equation, in the same way that Euclidean geometry is natural for the standard Laplacian.

Now let  $F$  be a finite set with at least two elements, and let  $F^\infty$  denote the set of sequences of elements of  $F$ . Given two elements  $x = \{x_i\}_{i=1}^\infty$  and  $y = \{y_i\}_{i=1}^\infty$  of  $F^\infty$  and a number  $a \in (0, 1]$  set

$$\begin{aligned} d_a(x, y) &= 0 && \text{when } x = y \\ &= a^j && \text{if } x_i = y_i \text{ for } i < j, x_j \neq y_j. \end{aligned} \quad (\text{B.2.10})$$

This is a metric for each  $a \in (0, 1]$ . In fact these are *ultrametrics*, which means that

$$d_a(x, z) \leq \max\{d_a(x, y), d_a(y, z)\} \quad (\text{B.2.11})$$

for all  $x, y, z \in F^\infty$ , which is much stronger than the triangle inequality. When  $a = 1$  (2.10) simply gives the discrete metric on  $F^\infty$ , so that distinct points in  $F^\infty$  have distance 1 from each other. For  $a < 1$  these metrics all determine the same topology, for which  $F^\infty$  is homeomorphic to the Cantor set. If  $F$  has exactly two elements and  $a = 1/3$ , then  $(F^\infty, d_a(x, y))$  is bi-Lipschitz equivalent to the standard Cantor set. For any  $a \in (0, 1)$  we can make a Cantor set construction in some  $\mathbb{R}^n$  which is bi-Lipschitz equivalent to  $(F^\infty, d_a(x, y))$  (with  $n \rightarrow \infty$  as  $a \rightarrow 1$ ).

Note that  $(F^\infty, d_a(x, y))$  is doubling when  $a < 1$  but not when  $a = 1$ . When  $0 < a < 1$  the metrics  $d_a(x, y)$  are all related to each other under the snowflake functor.

Cantor sets are totally disconnected. There are some amusing sets of intermediate connectivity. The first is often called the *Sierpinski carpet*. Let  $Q$  denote the unit square  $[0, 1] \times [0, 1]$  in the plane. We can decompose  $Q$  into 9 closed subsquares  $Q_i$  in the obvious manner, so that they each have sidelength  $1/3$ . Let us throw away the square  $Q_5$  in the center of  $Q$  and keep the remaining eight squares  $Q_i$ , and let  $K$  denote the subset of  $Q$  which is the union of these eight squares. Now apply this same process  $Q \rightarrow K$  to the eight squares in  $K$  to get a new compact subset  $K_2$  of  $Q$  which is the union of 64 squares of sidelength  $1/9$ . Repeating this process indefinitely we get compact sets  $K_l$  of  $Q$  which consist of  $8^l$  subsquares of  $Q$  with disjoint interiors and with sidelength  $3^{-l}$ . The Sierpinski carpet is the intersection of all these sets  $K_l$ . This is very similar to the construction of the Cantor set, but it gives a set which is pathwise connected.

Another amusing set in this vein is the *Sierpinski gasket*. This is obtained by taking an equilateral triangle  $T$  (instead of a square), decomposing it into 4 equilateral triangles of the same size, throwing away the middle triangle and keeping the remaining three, and then repeating the process indefinitely. The Sierpinski gasket itself is the intersection of the sequence of compact sets obtained in this manner, and it is also pathwise connected. However there are not as many paths connecting pairs of points in the Sierpinski gasket as in the Sierpinski carpet.

One can also make fractal versions of trees using the same construction. Let  $Q$  and  $Q_i$  be as before, and this time consider the set  $E$  which is the union of the five squares  $Q_i$  which are either the central square or one of the four corners of  $Q$ . Repeat the process  $Q \rightarrow E$  to get compact subsets

$E_j$  of  $Q$ , where each  $E_j$  is the union of  $5^j$  squares of sidelength  $3^{-j}$ . The intersection of all the  $E_j$ 's gives a fractal version of a tree.

Next we consider the Heisenberg group  $H_n$  and a natural metric on it. As a set  $H_n$  is  $\mathbb{C}^n \times \mathbb{R}$ , and the group operation  $(z_1, \dots, z_n, t)(z'_1, \dots, z'_n, t') = (z_1 + z'_1, \dots, z_n + z'_n, +t' + 2 \operatorname{Im} \sum_{j=1}^n z_j \bar{z}'_j)$  is defined as

$$\left( z_1 + z'_1, \dots, z_n + z'_n, +t' + 2 \operatorname{Im} \sum_{j=1}^n z_j \bar{z}'_j \right). \quad (\text{B.2.12})$$

This defines a noncommutative nilpotent group. There is a natural family of dilations on  $H_n$ , namely the mappings  $\delta_r : H_n \rightarrow H_n$  defined by  $\delta_r(z_1, \dots, z_n, t) = (r z_1, \dots, r z_n, r^2 t)$ ,  $r > 0$ . These dilations preserve the group structure (2.12). In this way they are analogous to ordinary dilations on Euclidean spaces.

This structure of group and dilations automatically determines a quasimetric on  $H_n$ . To understand this we start with the “homogeneous norm”

$$\|(z_1, \dots, z_n, t)\| = \left( \sum_{j=1}^n |z_j|^2 + |t| \right)^{\frac{1}{2}}. \quad (\text{B.2.13})$$

This quantity has the property that

$$\|\delta_r(x)\| = r \|x\| \quad (\text{B.2.14})$$

for all  $x \in H_n$  and  $r > 0$ , and also that

$$\|x^{-1}\| = \|x\| \quad (\text{B.2.15})$$

for all  $x \in H_n$ , where  $x^{-1}$  denotes the inverse of  $x$  in  $H_n$ . (If  $x = (z_1, \dots, z_n, t)$ , then  $x^{-1} = (-z_1, \dots, -z_n, -t)$ .) For our purposes the specific form of  $\|\cdot\|$  does not matter, what matters is that it satisfies (2.14) and (2.15), and that it is continuous and positive away from the origin. Any function on  $H_n$  with these properties will be bounded above and below by constant multiples of  $\|\cdot\|$ . We use this homogeneous norm to define a quasimetric on  $H_n$  by

$$d(x, y) = \|x^{-1} y\|. \quad (\text{B.2.16})$$

This is symmetric because of (2.15), it is clearly nonnegative and vanishes exactly when  $x = y$ , and it is not hard to check that it satisfies the approximate triangle inequality (2.1).

This quasimetric has important symmetry properties. If  $a \in H_n$  let  $\lambda_a : H_n \rightarrow H_n$  denote the mapping of left translation by  $a$  (with respect to the

group structure), so that  $\lambda_a(x) = a x$ . Our quasimetric  $d(x, y)$  is invariant under left translations,  $d(\lambda_a(x), \lambda_a(y)) = d(x, y)$  for all  $x, y, a \in H_n$ . It also behaves well under dilations,

$$d(\delta_r(x), \delta_r(y)) = r d(x, y) \quad (\text{B.2.17})$$

for all  $x, y \in H_n$  and all  $r > 0$ .

Notice that  $d(x, y)$  is compatible with the Euclidean topology on  $H_n$ . Any other quasimetric on  $H_n$  which is compatible with the Euclidean topology and which has the same behavior under translations and dilations is practically the same as  $d(x, y)$ , i.e., is bounded above and below by constant multiples of  $d(x, y)$ .

The Heisenberg geometry is somewhat similar to that of the metric in (2.9). They both respect the parabolic dilations  $\delta_r$  for instance. At the origin the Heisenberg geometry looks very much like the geometry of the metric in (2.9). This is true at other points in  $H_n$  too, except that the “axes” have to be tilted. This tilting is performed by the Heisenberg group action, and there is substantial twisting of the axes as one moves from point to point, because of the nontrivial nature of the group structure.

Is the quasimetric  $d(x, y)$  actually a metric, i.e., does it satisfy the triangle inequality? I am not certain, but it does not really matter. What does matter is that there is a metric  $d'(x, y)$  on  $H_n$  which is bounded above and below by constant multiples of  $d(x, y)$ . For instance we would get a metric if we replaced (2.13) with

$$\left( \sum_{j=1}^n |z_j|^4 + t^2 \right)^{\frac{1}{4}}.$$

See [Kor-Rei]. Do not get lost in the formulas here, there is a simple geometric reason for there to exist such a metric  $d'(x, y)$ . To understand this we should specify first a certain distribution of hyperplanes in the tangent spaces of points in  $H_n$ . At the origin we identify the tangent space of  $H_n$  with  $\mathbb{C}^n \times \mathbb{R}$  in the obvious manner, and we take the hyperplane  $\mathbb{C}^n \times \{0\}$ . At a general point  $x \in H_n$  we choose the hyperplane in the tangent space to  $H_n$  at  $x$  which is the image under the differential of  $\lambda_x$  of the hyperplane at the origin. This defines a smooth distribution of hyperplanes in the tangent bundle of  $H_n$ , and it turns out that this distribution is completely nonintegrable, so that every pair of points can be connected by a smooth curve which remains tangent to this distribution of hyperplanes. We can get an interesting metric on  $H_n$  by taking the infimum of the lengths of the curves that connect a given pair of points and which are always tangent to our distribution of hyperplanes. This is our metric  $d'(x, y)$ . It is

clearly larger than the Euclidean metric, but it turns out that it is compatible with the Euclidean topology too, which amounts to saying that it is bounded on compact subsets of  $H_n$ . Once we know this we can conclude that it is bounded above and below by constant multiples of  $d(x, y)$  because it has the correct invariance properties. These invariance properties follow from corresponding symmetries of our hyperplane distribution. The invariance of the hyperplane distribution under left translations follows from the definition, but for the dilations it is a fact to be checked.

It is easy to see that the Heisenberg group is doubling. For the unit ball centered at the origin this is clear, just a matter of compactness, and the general case can be reduced to that of the unit ball using translations and dilations.

Let us now look back at the preceding examples of metric spaces as a whole. A basic point to observe is that these spaces have a lot of symmetry to them, symmetry in terms of both location and scale. “Self-similarity” might be a better description. On Euclidean spaces we have the Euclidean metric which is invariant under translations and which scales properly under dilations. The parabolic metric (2.9) enjoys similar features, as does the Heisenberg group. What about our symbolic Cantor set  $F^\infty$ , the infinite product of a given finite set  $F$ ? Let  $\Sigma$  denote the group of permutations on  $F^\infty$  which come from permuting the coordinates separately, so that  $\Sigma$  is an infinite product of copies of the group of permutations on  $F$ . This group acts on  $F$  in such a way as to preserve the metric given by (2.10) (no matter the choice of  $a$ ). More generally a mapping  $\sigma$  from  $F^\infty$  onto itself will preserve the metric when  $\sigma$  has the property that if  $x \in F^\infty$  and  $y = \sigma(x)$ , then  $y_j$  depends only on  $x_1, \dots, x_j$  and not on  $x_i$  for  $i > j$ . Thus  $F^\infty$  has a large group of isometries, which we can think of as being like translations, and indeed this group of isometries is transitive. One also has analogues of dilations, namely shift mappings. This would work better on the “unbounded” version of  $F^\infty$ , in which we take doubly infinite sequences of elements of  $F$ , for then the left and right shift mappings would be bijections. As it is the left shift is not one-to-one and to define a right shift we have to make a choice for the first coordinate. In any case these shifts behave fairly well with respect to the metric in (2.10), and if we were to use doubly infinite sequences then the shifts would enjoy a scaling property like (2.17). Thus  $F^\infty$  has almost as much symmetry as the other examples, except that the symmetries are discrete.

The fractal examples, the Sierpinski carpet and gasket and the fractal tree, have also a lot of symmetry but not quite as much. Instead of thinking in terms of groups for these examples it is easier to think about a more limited kind of self-similarity. Let us start with the Sierpinski carpet. Fix

a point  $x$  in it and a positive integer  $j$ . At the  $j^{\text{th}}$  stage of the construction the Sierpinski carpet is a union of  $8^j$  squares of sidelength  $3^{-j}$ . Fix one of these squares that contains  $x$ , call it  $P$ . The construction of the Sierpinski carpet is made so that the intersection of  $P$  with the Sierpinski carpet is an exact replica of the whole Sierpinski carpet, but scaled by a factor of  $3^{-j}$ . The same phenomena occurs with the Sierpinski gasket and the fractal tree described above.

So let us try to have less symmetry, starting with  $F^\infty$ . Instead of taking an infinite product of copies of the same finite set, let us use a sequence of finite sets  $\{F_j\}$ , each with at least two elements. We can still define the metrics  $d_a(x, y)$  as in (2.11). We can still get plenty of isometries with respect to these metrics by taking infinite products of permutations on the  $F_j$ 's, for instance, but if the  $F_j$ 's are not all the same and do not follow any periodic pattern then we cannot build shift mappings in the same manner as before. The metrics will be different at different scales.

We could define more complicated metrics than the  $d_a(x, y)$ 's in order to break the symmetry that remains (coming from the permutations).

What about the doubling property? For the metrics  $d_a(x, y)$  in (2.9), say, with  $0 < a < 1$ . It is not hard to see that the new version of  $F^\infty$  obtained from the sequence  $\{F_j\}$  will be doubling if and only if the number of elements of the  $F_j$ 's is uniformly bounded.

The doubling condition can be seen as a much weaker cousin of self-similarity. Instead of saying that the space looks the same at all scales and locations, the doubling condition says that geometries that occur at different scales and locations in the space lie in a bounded family. This boundedness is not very strong. In the preceding example we could construct an interesting space from any bounded sequence of positive integers  $> 1$  (the cardinalities of the  $F_j$ 's). Self-similarity would correspond in this construction to periodic sequences.

Similarly we could modify the constructions of the Sierpinski carpet and gasket or the fractal tree so they are not so self-similar.

Note that the snowflake functor does not disturb the self-similarity properties that we have been discussing. In the next section we describe another way to deform the geometry of metric spaces.

### B.3. Doubling measures and regular metric spaces, deformations of geometry, Riesz products and Riemann surfaces.

The next definition provides a notion of compatibility between measures and metrics.

**B.3.1. Definition:** Let  $(M, d(x, y))$  be a metric space. A positive Borel

measure  $\mu$  on  $M$  is said to be doubling if there exists a constant  $C > 0$  so that

$$\mu(2B) \leq C\mu(B) \quad (\text{B.3.2})$$

for all balls  $B$  in  $M$  (and if  $\mu$  is not identically zero). Here  $2B$  denotes the ball with the same center as  $B$  but twice the radius.

A basic example of a doubling measure is Lebesgue measure on a Euclidean space. We shall give more examples soon.

There is nothing magical about the number 2 in (3.2), any number larger than 1 would work just as well. For instance, we can always iterate (3.2) to obtain

$$\mu(2^k B) \leq C^k \mu(B) \quad (\text{B.3.3})$$

for all positive integers  $k$ .

We shall use doubling measures to deform geometries. Before we get to that let us record a nice fact.

**B.3.4. Lemma:** *If  $(M, d(x, y))$  is a metric space which admits a doubling measure  $\mu$ , then  $(M, d(x, y))$  is doubling as a metric space.*

To see this fix a ball  $B$  in  $M$  with radius  $r$  say. Let  $A$  be a finite set of points in  $B$  such that  $d(x, y) \geq r/2$  for all  $x, y \in A$ ,  $x \neq y$ . Then  $A$  can have at most  $K$  elements, where  $K$  depends on the doubling constant but not on anything else. To see this consider the balls  $B(x) = B(x, r/4)$ ,  $x \in A$ . Our assumption on  $A$  implies that these balls are pairwise disjoint, and they are all contained in  $2B$ . Thus

$$\sum_{x \in A} \mu(B(x)) \leq \mu(2B). \quad (\text{B.3.5})$$

However the doubling condition (iterated as in (3.3)) implies that  $\mu(B(x))$  is bounded from below by a constant multiple of  $\mu(2B)$  for each  $x \in A$ . Thus (3.5) implies a bound on the number of elements of  $A$ .

Since we have a bound on the number of elements of any such set  $A$  we can take one which has a maximal number of elements. Maximality implies that if  $z \in B$  then  $d(x, z) < r/2$  for some  $x \in A$ . Thus the balls  $B(x, r/2)$ ,  $x \in A$ , cover  $B$ . This implies the doubling condition, and Lemma 3.4 follows.

Now let us use doubling measures to deform geometry. Let  $(M, d(x, y))$  be a metric space, let  $\mu$  be a doubling measure on  $M$ , and let  $\alpha > 0$  be given. Set

$$D(x, y) = \{\mu(\overline{B}(x, d(x, y))) + \mu(\overline{B}(y, d(x, y)))\}^\alpha \quad (\text{B.3.6})$$

If  $M = \mathbb{R}^n$  and  $\alpha = 1/n$ , then  $D(x, y)$  gives back a constant multiple of the Euclidean metric. In general we want to think of  $D(x, y)$  as defining a new geometry on  $M$ .

The definition of  $D(x, y)$  may look a little strange. On a Euclidean space we could simply take the  $\mu$ -measure of the smallest closed ball that contains  $x$  and  $y$  instead of the  $\mu$ -measure of the balls  $B(x, d(x, y))$ ,  $B(y, d(x, y))$ , but on a general metric space it is more convenient to do the latter. All variations on this theme are practically equivalent, because of the doubling condition.

**B.3.7. Lemma:** *Under the assumptions above,  $D(x, y)$  defines a quasimetric on  $M$ .*

This is not hard to check, using the doubling condition on  $\mu$ . Typically we do not get a metric, but remember that for each quasimetric we can find a metric as in (2.2).

To understand better this idea of making quasimetrics from doubling measures let us consider the case when the new geometry is essentially the same as the old one.

**B.3.8. Definition:** *A metric space  $(M, d(x, y))$  is said to be (Ahlfors) regular of dimension  $s$  if it is complete and if there is a positive Borel measure  $\mu$  on  $M$  and a constant  $C > 0$  so that*

$$C^{-1} r^s \leq \mu(B(x, r)) \leq C r^s \quad (\text{B.3.9})$$

for all  $x \in M$  and all  $0 < r \leq \text{diam } M$ .

In this case the quasimetric  $D(x, y)$  is bounded above and below by constant multiples of  $d(x, y)$  if we take  $\alpha = 1/s$ . The requirement of completeness in Definition 3.8 is not needed for this fact, but it is convenient in practice.

It turns out that the measure  $\mu$  in Definition 3.8 does not play a sensitive role, in the following sense. If a metric space  $M$  is regular with dimension  $s$ , then any two measures which satisfy conditions like (3.9) are each bounded by constant multiples of each other, and  $s$ -dimensional Hausdorff measure on  $M$  will also satisfy a condition like (3.9).

To get examples of regular metric spaces we can follow our discussion of examples of metric spaces in the preceding section. Euclidean spaces are regular with  $s$  equal to their ordinary dimension and  $\mu$  taken to be Lebesgue measure. If  $(M, d(x, y))$  is a regular metric space of dimension  $s$ , and if we apply the snowflake functor to get the metric space  $(M, d(x, y)^t)$ , then this new metric space is also regular, with dimension  $s/t$ .

If we take the parabolic metric (2.9) on  $\mathbb{R}^{n+1}$ , then we get a regular metric space of dimension  $n + 2$ , with  $\mu$  taken to be Lebesgue measure.

The Heisenberg group  $H_n$  with the geometry discussed in Section 2 is regular with dimension  $2n + 2$ , again taking  $\mu$  to be Lebesgue measure. This uses the easy fact that Lebesgue measure is invariant under translations with respect to the group structure (2.12).

Let  $F$  be a finite set with  $n \geq 2$  elements and let  $F^\infty$  be the space of sequences with values in  $F$ , as in Section 2. Let  $\nu$  denote the uniform probability measure on  $F$ , which assigns to each element of  $F$  the measure  $1/n$ . Let  $\mu$  denote the probability measure on  $F^\infty$  obtained by taking the product of infinitely many copies of  $\nu$ . Then  $(F^\infty, d_a(x, y))$  is a regular metric space when  $0 < a < 1$ , with this choice of  $\mu$ , and with the dimension  $s$  determined by the formula  $a^s = 1/n$ . Note that  $s$  runs through all of  $(0, \infty)$  as  $a$  runs through  $(0, 1)$ .

Suppose that  $Z$  is the Sierpinski carpet, as described in Section 2. Then  $Z$  is regular with dimension  $s$ , where  $s$  satisfies  $3^{-s} = 1/8$ . This is because there is a natural probability measure  $\mu$  on  $Z$  with the property that if  $P$  is one of the  $8^j$  squares of sidelength  $3^{-j}$  obtained at the  $j^{\text{th}}$  stage of the construction of  $Z$ , then  $\mu(P) = 8^{-j}$ .

Similarly, the Sierpinski gasket and the fractal tree described in Section 2 are both regular, and they admit measures  $\mu$  analogous to the one just described.

Now let us consider some examples of doubling measures with less symmetry.

On  $\mathbb{R}^n$  take the measure  $\mu = |x|^a dx$ , where  $a > -n$  and  $dx$  denotes Lebesgue measure. This is doubling. We can also take  $\mu = |x_1|^a dx$  on  $\mathbb{R}^n$ , where  $a > -1$ .

Let  $K$  denote the usual middle-thirds Cantor set on  $\mathbb{R}$  and set  $\mu = \text{dist}(x, K)^a dx$ . This defines a doubling measure on  $\mathbb{R}$  for positive values of  $a$  and also some negative values (in a range which can be computed explicitly).

These examples are all absolutely continuous with respect to Lebesgue measure. Can a doubling measure on a Euclidean space be singular? The answer turns out to be yes. To see this we use *Riesz products*, a kind of multiplicative (lacunary) Fourier series. Let  $\{a_j\}_{j=1}^\infty$  be a sequence of real numbers such that  $|a_j| \leq 1$  for each  $j$ . Define a measure  $\mu$  on  $\mathbb{R}$  by

$$\mu = \prod_{j=1}^{\infty} (1 + a_j \cos 3^j x). \quad (\text{B.3.10})$$

This definition requires some explanation. This infinite product should be

interpreted as the limit of the finite products

$$\prod_{j=1}^n (1 + a_j \cos 3^j x) \quad (\text{B.3.11})$$

as  $n \rightarrow \infty$ , with the limit taken in the sense of distributions. It is not hard to check that this limit exists, by multiplying out the product and then writing it as a Fourier series. (See Theorem 7.5 on p. 209 of [Zyg].) The main point is that each term in the Fourier series arises only once as a term in the expanded product. The distributional limit of (3.11) need not be a function in general, but it always is a measure, and this comes down to the fact that each of the functions in (3.11) is nonnegative. One can also show that the limiting measure  $\mu$  is doubling if  $\sup_j |a_j| < 1$ . This is approximately what is shown in the last section of [Beur-Ahl], but unfortunately [Beur-Ahl] does not quite correspond to our present requirements. Let us sketch the main points. Suppose that  $I$  is an interval in  $\mathbb{R}$ , and we want to show that  $\mu(2I) \leq C\mu(I)$ . This is trivial if  $I$  has length  $\geq 2\pi/3$ , because  $\mu$  is periodic with period  $2\pi/3$ . Suppose that  $|I| < 2\pi/3$ , and let  $k$  be the smallest positive integer such that  $|I| > 2\pi/3^k$ . Write

$$\begin{aligned} \mu &= \prod_{j=1}^{k-1} (1 + a_j \cos 3^j x) \cdot \mu_k, \quad \text{where} \\ \mu_k &= \prod_{j=k}^{\infty} (1 + a_j \cos 3^j x), \end{aligned} \quad (\text{B.3.12})$$

and where this last infinite product is interpreted in the same manner as before. We have that  $\mu_k$  is periodic with period  $2\pi/3^k < |I|$ . One can also check that

$$\sup_{2I} \prod_{j=1}^{k-1} (1 + a_j \cos 3^j x) \leq C \inf_{2I} \prod_{j=1}^{k-1} (1 + a_j \cos 3^j x) \quad (\text{B.3.13})$$

with a constant  $C$  that does not depend on  $I$ . Let us sketch the proof of this. Each factor  $1 + a_j \cos 3^j x$  is uniformly bounded and bounded away from 0 on  $\mathbb{R}$ , because of our assumption that  $\sup_j |a_j| < 1$ . Thus no finite number of these factors matter for (3.13), but the problem for (3.13) is that there are infinitely many of them. On the other hand,

$$|\cos 3^j x - \cos 3^j y| \leq 3^j 2|I| \leq 4\pi 3^{j-k+1} \quad (\text{B.3.14})$$

whenever  $x, y \in 2I$ . The first inequality follows from the mean value theorem, the second from our choice of  $k$  (to be as small as possible). For

$j \leq k - 1$  the left side behaves like a convergent geometric series. Using this estimate and the fact that each factor  $1 + a_j \cos 3^j x$  is bounded and bounded away from 0 it is not difficult to verify (3.13). Once we have (3.13) it is easy to check that  $\mu(2I) \leq C\mu(I)$  using (3.12) and the fact that  $\mu_k$  is periodic with period  $< |I|$ .

Thus the Riesz product (3.10) defines a doubling measure on  $\mathbb{R}$ . See also 8.8 (a) on p.40 of [Stein]<sub>HA</sub>.

It turns out that the Riesz product (3.10) is completely singular with respect to Lebesgue measure if  $\sum_j a_j^2 = \infty$ . (See Theorem 7.6 on p.209 of [Zyg].) Thus there are doubling measures on  $\mathbb{R}$  which are completely singular, i.e., have no absolutely continuous part with respect to Lebesgue measure. We can get these measures to be self-similar by taking all the  $a_j$ 's to be the same. On the other hand we can get singular doubling measures that are a little bit smoother by taking a sequence  $\{a_j\}$  which tends to 0.

We can also obtain singular doubling measures on any  $\mathbb{R}^n$  by taking products. (In general Cartesian products of doubling measures are doubling.)

There are doubling measures on  $\mathbb{R}$  (and hence on  $\mathbb{R}^n$ ) of the form  $\mu = \omega(x) dx$  where  $\omega(x)$  is the characteristic function of a set whose complement has positive measure. Such a  $\mu$  is absolutely continuous with respect to Lebesgue measure but not the other way around. See 8.8 (b) on p.40 of [Stein]<sub>HA</sub>.

Now let us describe a class of singular doubling measures on  $\mathbb{R}$  which arise from Riemann surfaces. Let  $S_1$  and  $S_2$  be two compact Riemann surfaces without boundary and with common genus  $g > 1$ . Let  $f : S_1 \rightarrow S_2$  be an orientation-preserving diffeomorphism which is not homotopic to a conformal mapping. By the uniformization theorem the universal covers of  $S_1$  and  $S_2$  are isomorphic as Riemann surfaces to the upper half-plane  $U = \{z \in \mathbb{C} : \operatorname{Im} z > 0\}$ . Let  $F : U \rightarrow U$  be obtained by lifting  $f : S_1 \rightarrow S_2$  to a mapping between the universal covers of  $S_1$  and  $S_2$  and then using the uniformizing isomorphisms to get to  $U$ . We can choose these uniformizing isomorphisms so that  $F(z) \rightarrow \infty$  when  $z \rightarrow \infty$  in  $U$  (this is just a normalization). It is well-known that  $F$  is a “quasiconformal” mapping, and that with this normalization  $F$  extends to a homeomorphism from  $\overline{U}$  to itself. In particular  $F$  induces a homeomorphism  $h : \mathbb{R} \rightarrow \mathbb{R}$ . The distributional derivative of this homeomorphism defines a locally finite measure  $\mu$  on  $\mathbb{R}$  (sometimes called the Lebesgue-Stieltjes measure associated to  $h$ ), and this measure  $\mu$  is doubling. (See [Beur-Ahl].) A version of the Mostow rigidity theorem implies that this measure  $\mu$  must be completely singular with respect to Lebesgue measure. (See [Agard].)

Thus we get another class of singular doubling measures on the line.

These doubling measures have a lot of self-similarity, coming from the groups of Möbius transformations associated to the uniformization of  $S_1$  and  $S_2$ . The nature of this self-similarity is amusingly different from that of the Riesz products (in the case where the  $a_j$ 's are all the same, say). There is no such group for the Riesz products.

See also [Bish–Steg] concerning the doubling measures that come from Riemann surfaces, and [Tukia] for another construction of singular doubling measures.

Next let us consider our symbolic Cantor sets again. Let  $F$  be a finite set with at least two elements, and let  $F^\infty$  denote the space of sequences which take values in  $F$ . Let  $\{\nu_j\}_{j=1}^\infty$  be a sequence of probability measures on  $F$ , and let  $\mu$  denote the probability measure on  $F^\infty$  which is their product. Let  $\epsilon > 0$  be given, and let us assume that each  $\nu_j$  has the property that it gives mass at least  $\epsilon$  to each point in  $F$ . Then  $\mu$  is a doubling measure on  $F^\infty$  with respect to any of the metrics  $d_a(x, y)$  defined in (2.10) with  $0 < a < 1$ . This is not hard to check. These measures are analogous to Riesz products. They will typically be singular with respect to the “uniform” measure that we defined on  $F^\infty$ .

Notice that we can obtain new doubling measures from old ones, by adding them, or taking products of doubling measures on products of metric spaces.

Keep in mind that we can use doubling measures to deform geometry on a space, as in (3.6), so that our examples should be seen also as examples of geometry. To put the relationship between geometry and measure into perspective let us consider a simple situation. Suppose that we are given a doubling measure  $\mu$  on  $\mathbb{R}^n$ , and assume that it is mutually absolutely continuous with respect to Lebesgue measure. This means that we can write  $\mu$  as  $\omega(x) dx$  for some positive locally integrable function  $\omega(x)$  on  $\mathbb{R}^n$ . The associated quasidistance  $D(x, y)$  defined in (3.6) with  $\alpha = 1/n$  is then approximately Euclidean most of the time. For instance, if  $z$  is a Lebesgue point of  $\omega$ , so that

$$\lim_{r \rightarrow 0} r^{-n} \int_{B(z, r)} |\omega(u) - \omega(z)| du = 0, \quad (\text{B.3.15})$$

then  $D(x, y)$  looks asymptotically like a multiple of the Euclidean metric near  $z$ . (Recall that almost every  $z \in \mathbb{R}^n$  is a Lebesgue point of  $\omega$ .) Thus  $(\mathbb{R}^n, D(x, y))$  is approximately Euclidean almost everywhere in this case. We shall encounter this idea again in Part III.

#### B.4. Quasisymmetric mappings and deformations of geometry from doubling measures.

The following definition provides a useful concept for comparing the geometry of two different metric spaces.

**B.4.1. Definition:** Let  $(M, d(x, y))$  and  $(N, \rho(x, y))$  be metric spaces. A mapping  $f : M \rightarrow N$  is said to be quasisymmetric if it is not constant and if there exists a homeomorphism  $\eta : [0, \infty) \rightarrow [0, \infty)$  such that for any points  $x, y, z \in M$  and  $t > 0$  we have that

$$d(x, y) \leq t d(x, z) \quad \text{implies that} \quad \rho(f(x), f(y)) \leq \eta(t) \rho(f(x), f(z)). \quad (\text{B.4.2})$$

We may sometimes say that  $f$  is  $\eta$ -quasisymmetric to be more precise. A basic reference for quasisymmetric mappings is [Tuk–Vais].

What does (4.2) mean? If  $y$  is much closer to  $x$  than  $z$  is, then we can take  $t$  to be very small, and we conclude that  $f(y)$  is much closer to  $f(x)$  than  $f(z)$  is (since  $\eta(t)$  will also be very small). In other words quasisymmetric mappings do not distort the *relative* size of distances very much, even though the distances themselves may be distorted tremendously. This should be compared with the bi-Lipschitz condition (2.7), which requires that the actual distances not be distorted very much. Bi-Lipschitz mappings are automatically quasisymmetric (with a linear choice of  $\eta$ ), but the converse is not true. A basic example of a quasisymmetric mapping is given by  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$ ,  $f(x) = |x|^a x$ ,  $a > -1$ . When  $a \neq 0$  this mapping distorts distances strongly near the origin and near infinity.

The quasisymmetry condition gives another way to say that the snapshots of a mapping are bounded, but with a different normalization than for bi-Lipschitz mappings. Namely we permit ourselves to rescale both domain and range when we take the snapshot.

It is not difficult to show that  $f$  is quasisymmetric if it satisfies (4.2) with  $\eta : [0, \infty) \rightarrow [0, \infty)$  not necessarily a homeomorphism but just a mapping which satisfies  $\eta(t) \rightarrow 0$  when  $t \rightarrow 0$  and which is bounded on bounded intervals. That is, one can always find a homeomorphism which is larger than such a given  $\eta$ . In practice this observation makes it easier to check that a mapping is quasisymmetric.

Roughly speaking, quasisymmetric mappings are mappings which may change the size of balls very much but not their shapes. This idea is illustrated by the following example. Let  $(M, d(x, y))$  be a metric space and let  $0 < s < 1$  be given. The identity mapping on  $M$  is quasisymmetric as a mapping from  $(M, d(x, y))$  to  $(M, d(x, y)^s)$  or vice-versa. The spaces  $(M, d(x, y))$  and  $(M, d(x, y)^s)$  have exactly the same classes of balls, they differ only in the radii of these balls.

Let us say that two metric spaces are *quasisymmetrically equivalent* if there is a quasisymmetric mapping from one onto the other. Note that the inverse of a quasisymmetric mapping from one metric space onto another is also quasisymmetric. This is not difficult to verify.

Another approximate statement is that quasisymmetric mappings understand the concept of expanding a ball by a bounded factor even if they do not understand the size of the radius of the ball, even to within a bounded factor. For instance, if two metric spaces are quasisymmetrically equivalent, then one is doubling if and only if the other one is. (Exercise.) Similarly, given two metric spaces and a quasisymmetric map from one onto the other, any measure on one can be pushed over to the other using the mapping, and this correspondence takes doubling measures to doubling measures.

In the previous section we saw how doubling measures can be used to deform the geometry of a space. We want to take a closer look at this deformation now. It will be convenient to make a mild nondegeneracy assumption about our metric spaces though.

**B.4.3. Definition:** A metric space  $(M, d(x, y))$  is said to be uniformly perfect if there is a constant  $C > 0$  so that for each  $x \in M$  and  $0 < r \leq \text{diam } M$  there is a point  $y \in M$  such that

$$C^{-1}r \leq d(x, y) \leq r. \quad (\text{B.4.4})$$

This condition prevents the occurrence of isolated points or even islands that are too isolated. All of the metric spaces described in Section 2 satisfy this condition.

Isolated points are not necessarily bad. The set of integers  $\mathbb{Z}$  equipped with the Euclidean metric is a quite reasonable space even though it consists only of isolated points. Isolated points can cause some nuisances for us though. For simplicity we shall require the uniformly perfect condition in order to avoid technical irritations, even though it is stronger than we really need.

Another way to state the uniformly perfect condition is to require that

$$\text{diam } B(x, r) \geq C^{-1}r \quad (\text{B.4.5})$$

whenever  $x \in M$  and  $r \leq \text{diam } M$ . (This constant need not be quite the same as the one above.)

It is not hard to imagine how the uniform perfectness condition can be useful in the context of doubling measures and quasisymmetric mappings. To use the hypothesis of quasisymmetry, for instance, one needs to have three points  $x, y, z$  in hand, and the uniformly perfect condition can help to provide these points.

There is a nice relationship between doubling measures and quasisymmetric geometry on uniformly perfect spaces.

**B.4.6. Proposition:** *If  $(M, d(x, y))$  is a uniformly perfect metric space and  $\mu$  is a doubling measure on  $M$ , and if  $D(x, y)$  is defined as in (3.6) (for any choice of  $\alpha > 0$ ), then the identity mapping on  $M$  is quasisymmetric as a mapping from  $(M, d(x, y))$  to  $(M, D(x, y))$ .*

Thus when we deform the geometry using a doubling measure, the new space remains quasisymmetrically equivalent to the original one.

The statement of the theorem is slightly illegal, since  $D(x, y)$  is only a quasimetric and quasisymmetric mappings were defined officially only for metric spaces, but this is not a serious issue.

The following is the main point.

**B.4.7. Lemma:** *Let  $(M, d(x, y))$  be a uniformly perfect metric space and let  $\mu$  be a doubling measure on  $M$ . Then there is a (small) constant  $a \in (0, 1)$  such that*

$$\mu(B(x, ar)) \leq (1 - a) \mu(B(x, r)) \quad (\text{B.4.8})$$

whenever  $x \in M$  and  $0 < r \leq \text{diam } M$ .

Compare this with (3.3), which says that measures of balls do not grow too fast as the radius is increased. This says that measures of balls decrease at a definite rate as the radius decreases. Indeed one can iterate (4.8) to get

$$\mu(B(x, a^k r)) \leq (1 - a)^k \mu(B(x, r)) \quad (\text{B.4.9})$$

for all  $x \in M$ ,  $0 < r \leq \text{diam } M$ , and positive integers  $k$ . This inequality implies in particular that  $\mu$  has no atoms, that sets with only one element always have measure 0. In general a doubling measure can have an atom only at an isolated point. (Note that counting measure on  $\mathbb{Z}$  is doubling.)

Let us prove the lemma. Let  $x \in M$  and  $0 < r \leq \text{diam } M$  be given. The requirement that  $M$  be uniformly perfect implies that there is a point  $y \in M$  such that  $2br \leq d(x, y) \leq r/2$  for some constant  $b$  that does not depend on  $x$  or  $r$ . Thus  $B(x, br)$  and  $B(y, br)$  are disjoint subsets of  $B(x, r)$ , and so

$$\begin{aligned} \mu(B(x, br)) &\leq \mu(B(x, r)) - \mu(B(y, br)) \\ &\leq \mu(B(x, r)) - C^{-1} \mu(B(x, r)) \end{aligned} \quad (\text{B.4.10})$$

for a suitable constant  $C$ , because of the doubling property for  $\mu$  (and the fact that  $B(x, r) \subseteq B(y, 2r)$ ). This implies (4.8), and the lemma follows.

Now let us see why Proposition 4.6 is true. It suffices to show that there exists a mapping  $\eta : [0, \infty) \rightarrow [0, \infty)$  such that  $\lim_{t \rightarrow 0} \eta(t) = 0$ ,  $\eta$  is bounded on bounded intervals in  $[0, \infty)$ , and such that

$$d(x, y) \leq t d(x, z) \quad \text{implies that} \quad D(x, y) \leq \eta(t) D(x, z). \quad (\text{B.4.11})$$

for any points  $x, y, z \in M$  and any  $t > 0$ . For  $t \geq 1$  one can get this kind of estimate using (3.3), the doubling condition for  $\mu$ , and the definition of  $D(x, y)$ . For  $t < 1$  one can derive the necessary bound from (4.9). In each case one can choose  $\eta(t)$  so that it is a constant multiple of a power of  $t$ , but one needs to use different powers for the different cases (a large power for large  $t$ , a small power for small  $t$ ). This proves Proposition 4.6, modulo details which we leave as an exercise.

Let us now continue with the same assumptions as in Proposition 4.6 and take a closer look at the  $D(x, y)$  balls. Our goal is to check that  $(M, D(x, y), \mu)$  automatically satisfies the Ahlfors regularity condition (3.9) with  $s = 1/\alpha$ . Fix  $x \in M$  and  $\rho > 0$  and consider the set

$$\beta(x, \rho) = \{y \in M : D(x, y) \leq \rho\}. \quad (\text{B.4.12})$$

(We shall continue to write  $B(x, r)$  for the balls with respect to  $d(x, y)$ .) It may be that  $\beta(x, \rho) = M$ , and if this is the case we require that  $\rho$  be chosen as small as possible with this property. The smallest such  $\rho$  will be comparable in size to the  $D(\cdot, \cdot)$ -diameter of  $M$ .

Choose  $r > 0$  as small as possible so that  $\beta(x, \rho) \subseteq \overline{B}(x, r)$ . Thus there is a point  $z \in \beta(x, \rho)$  such that  $d(x, z) > r/2$ . Using (4.11) we get that

$$B(x, C^{-1}r) \subseteq \beta(x, \rho) \subseteq \overline{B}(x, r) \quad (\text{B.4.13})$$

for a suitable constant  $C$  which does not depend on  $x$ ,  $z$ , or  $\rho$ .

Let us check that

$$C^{-1}\rho \leq \mu(B(x, r))^\alpha \leq C\rho \quad (\text{B.4.14})$$

for a suitable constant  $C > 0$ , where  $\alpha > 0$  was used in the definition of  $D(x, y)$ , as in the statement of Proposition 4.6. The upper bound follows from the fact that

$$\rho \geq D(x, z) \geq \mu(B(x, d(x, z)))^\alpha \geq \mu(B(x, r/2))^\alpha \quad (\text{B.4.15})$$

and the doubling condition for  $\mu$ . To get the lower bound we use the requirement that  $M$  be uniformly perfect to obtain a point  $w \in M$  such

that  $r < d(x, w) \leq Cr$  for some constant  $C$ . (Small lie, but wait a moment.) Our choice of  $r$  ensures that  $D(x, w) \geq \rho$ . Going back to the definition (3.6) we obtain the lower bound in (4.14) using also the doubling condition for  $\mu$ . This argument does not work in the case where  $Cr \geq \text{diam } M$ , because then the uniformly perfect condition does not provide us with such a point  $w$ . In this case  $\mu(B(x, r))$  is approximately the same as  $\mu(M)$ , because of the doubling condition, and then the lower bound in (4.15) follows because  $\rho$  is never larger than the  $D(\cdot, \cdot)$ -diameter of  $M$ .

From (4.14), (4.13), and the doubling condition on  $\mu$  we obtain that

$$C^{-1}\rho \leq \mu(\beta(x, \rho))^\alpha \leq C\rho. \quad (\text{B.4.16})$$

There is a minor technical point of measurability of  $\beta(x, \rho)$ , but this is not serious. Thus we see that  $(M, D(x, y))$  satisfies the regularity condition (3.9) with dimension  $1/\alpha$ , modulo the fact that  $D(x, y)$  is not necessarily a metric but only a quasimetric, and the fact that  $D(x, y)$  may not be complete. The first issue can be avoided using (2.2). As to the second, one can check that  $(M, D(x, y))$  is complete if and only if  $(M, d(x, y))$  is.

Notice, by the way, that if a metric space is doubling and complete, then all of its closed and bounded subsets are compact. This follows from the well-known result that a metric space is compact if and only if it is complete and totally bounded. (The latter means that for each  $\epsilon > 0$  the space can be covered by finitely many balls of radius  $\epsilon$ .)

### B.5. Rest and recapitulation.

The doubling condition for metric spaces provides a way to say that the space has bounded snapshots. The Lipschitz, bi-Lipschitz, and quasisymmetry conditions are boundedness conditions for snapshots of mappings. The doubling condition for a measure says that its snapshots are bounded.

Using doubling measures we can deform the geometry of metric spaces. Under mild technical conditions this deformation is quasisymmetrically equivalent to the original space, so that the class of balls is approximately preserved, just the radii are changed. This is a variant of the idea of conformal deformations in Riemannian geometry.

In Section III. we shall consider the extent to which Lipschitz, bi-Lipschitz, and quasisymmetric mappings have hidden rigidity, or conditions under which spaces have hidden rigidity. These rigidity properties will have a measure-theoretic flavor to them. Something special happens, not uniformly at all points, only for 90% of them, something like that.

These rigidity phenomena do not happen all the time, just under certain circumstances. It is not understood exactly when they should occur or what form they should take.

In the Section II. we look at general facts about spaces and mappings which enjoy bounds on their snapshots, and another concept of bounded snapshots.

## II. Analysis on general spaces

### B.6. Hölder continuous functions on metric spaces.

**B.6.1. Definition:** Let  $(M, d(x, y))$  and  $(N, \rho(u, v))$  be metric spaces and let  $\alpha > 0$  be given. We say that  $f : M \rightarrow N$  is Hölder continuous of order  $\alpha$  if there is a constant  $K > 0$  so that

$$\rho(f(x), f(y)) \leq K d(x, y)^\alpha \quad (\text{B.6.2})$$

for all  $x, y \in M$ . In the case where  $N$  is the real line with the standard metric we call  $f$  a Hölder continuous function of order  $\alpha$  and we denote the space of all of these by  $\Lambda_\alpha$ .

We shall sometimes say that “ $f$  is Hölder continuous of order  $\alpha$  with constant  $K$ ” to make the bound explicit. If we say “Hölder continuous function” (instead of mapping) we shall mean a mapping into the real numbers.

When  $\alpha = 1$  we have already christened this the Lipschitz condition, but the latter is special and deserves a special name. Traditionally one does not consider  $\alpha > 1$  because on many spaces Hölder continuous functions of order  $\alpha > 1$  are all constant. This happens on Euclidean spaces, for instance, because Hölder continuity of order  $\alpha > 1$  implies that the first derivatives of the function exist and vanish everywhere.

Notice that if we replace  $(M, d(x, y))$  with the snowflake  $(M, d(x, y)^\alpha)$  then (6.2) becomes simply the Lipschitz condition with respect to the new metric. So all theorems about Lipschitz functions on metric spaces apply to Hölder continuous functions. The reverse fails in a strong way, as we shall see.

Typically when there are plenty of functions which satisfy a condition like (6.2) with  $\alpha > 1$  it means that the space that we are working on is already the result of applying the snowflake functor to a metric space. One can formulate precise versions of this statement which are easy to prove.

Can we build plenty of Hölder continuous functions on a metric space? Can we build plenty of Lipschitz functions for that matter? The simple answer to the second question is yes, and we can build them using the fact that the metric  $d(x, y)$  is Lipschitz in each variable. (This uses the triangle

inequality and does not work for quasimetrics.) By the snowflake remark above we can build Hölder continuous functions of order  $\alpha < 1$  at least as easily as we can build Lipschitz functions, but it turns out that there are more flexible constructions available too. The basic information of this type is contained in the following.

**B.6.3. Theorem:** *Let  $(M, d(x, y))$  be a metric space and let  $0 < \alpha < 1$  be given. Let  $k > 1$  be some constant, and suppose that we have a family of functions  $\{f_j\}_{j \in \mathbb{Z}}$ ,  $f_j : M \rightarrow \mathbb{R}$ , such that*

$$\sup_M |f_j| \leq k 2^{j\alpha}, \quad (\text{B.6.4})$$

$$f_j \text{ is } k 2^{j(\alpha-1)}\text{-Lipschitz,} \quad (\text{B.6.5})$$

$$\sum_{j \in \mathbb{Z}} f_j(x_0) \quad \text{converges for some } x_0 \in M. \quad (\text{B.6.6})$$

Then  $\sum_{j \in \mathbb{Z}} f_j(x)$  converges uniformly on bounded subsets of  $M$  to a function  $f$  which is Hölder continuous of order  $\alpha$ . Conversely, every Hölder continuous function of order  $\alpha$  on  $M$  admits such a representation.

What on earth does this mean? Let us check first the following fact.

**B.6.7. Lemma:** *Suppose that  $0 < \alpha < 1$  and that  $f : M \rightarrow \mathbb{R}$  satisfies*

$$\sup_M |f| \leq k t^\alpha, \quad (\text{B.6.8})$$

$$f \text{ is } k t^{(\alpha-1)}\text{-Lipschitz,} \quad (\text{B.6.9})$$

for some  $k, t > 0$ . Then  $f$  is Hölder continuous of order  $\alpha$ , with constant  $2k$ .

The point here is that the constant does not depend on  $t$ , only on  $k$ . Before we pursue this matter let us quickly check the lemma. Let  $x, y \in M$  be given. We need to estimate  $|f(x) - f(y)|$ . If  $x$  and  $y$  are close together then we should use the Lipschitz condition (6.9). When they are far apart we should use the bound (6.8). Specifically, if  $d(x, y) \leq t$ , then (6.9) implies that

$$|f(x) - f(y)| \leq k t^{(\alpha-1)} d(x, y) \leq k d(x, y)^\alpha. \quad (\text{B.6.10})$$

If  $d(x, y) \geq t$ , then we get

$$|f(x) - f(y)| \leq 2 \sup_M |f| \leq 2 k t^\alpha \leq 2 k d(x, y)^\alpha. \quad (\text{B.6.11})$$

Thus we get the Hölder continuity condition (6.2) in either case. This proves Lemma 6.7.

The precise choices of parameters in (6.4), (6.5), (6.8), and (6.9) may have seemed odd, but hopefully the point of these choices makes better sense now. We are making the right normalizations to get functions which are Hölder continuous of order  $\alpha$  with a uniform bound. Think of the  $t$  in Lemma 6.7 as defining the scale at which the real action takes place. At larger scales the function is sort of boring because (6.8) implies that it is too small to be interesting. At smaller scales the function is rather smooth, because of (6.9).

For a function on the real line, think of the Lipschitz condition as meaning that the derivative of the function is bounded. Think of Hölder continuity of order  $\alpha$  as meaning something like the “derivative of order  $\alpha$ ” is bounded. If you want to switch from a derivative of order  $\alpha$  to a derivative of order 1, you have to pay for it. If the function is smooth at the scale of  $t$ , then you should pay by having a norm which looks like  $t^{(\alpha-1)}$ .

If we were working with functions on the real line, then we would think of functions  $f$  as in Lemma 6.7 as being Hölder continuous functions of order  $\alpha$  whose Fourier transform is concentrated in the range of frequencies of size  $t^{-1}$ . On a general metric space we can still think of a function  $f$  as in Lemma 6.7 as being a function whose “frequencies” are concentrated in the range of  $t^{-1}$ , but now this is more of an idea than a precise statement.

In Theorem 6.3 the functions  $f_j$  should be viewed as functions which live at the scale of  $2^j$ , whose frequencies are mostly of the size of  $2^{-j}$ .

These words reflect a well-developed area of Harmonic Analysis called Littlewood-Paley theory.

Theorem 6.3 says that every Hölder continuous function on  $M$  can be decomposed into pieces living at the scale of  $2^j$ ,  $j \in \mathbb{Z}$ , and that such pieces can be combined in an arbitrary manner to get a Hölder continuous function of order  $\alpha$ . Let us pause a moment to appreciate this. Lemma 6.7 implies that each of the  $f_j$ 's in Theorem 6.3 is Hölder continuous of order  $\alpha$  with a constant that does not depend on  $j$ , but these Hölder constants do not have to be anything more than bounded. We cannot control the Hölder constant of  $\sum_j f_j$  by summing the Hölder constants of the individual pieces, because these individual Hölder constants need not be any more than bounded. Thus we are getting a kind of orthogonality which implies that an infinite sum of bounded objects is bounded even when the sum of the norms is infinite. The point is that the various scales are more-or-less independent of each other, so that the  $f_j$ 's do not really interact much.

The condition (6.6) is just a normalization and should not be taken too seriously.

Let us now proceed to the proof of Theorem 6.3. Assume first that  $\{f_j\}$  is given as in the theorem, and we want to prove that  $\sum_j f_j$  is Hölder continuous. The following is the main point.

**B.6.12. Lemma:** *If  $0 < \alpha < 1$  and  $\{f_j\}$  satisfies (6.4) and (6.5), then*

$$\sum_{j \in \mathbb{Z}} |f_j(x) - f_j(y)| \leq C(\alpha) k d(x, y)^\alpha \quad (\text{B.6.13})$$

for all  $x, y \in M$ .

This constant  $C(\alpha)$  depends only on  $\alpha$  and it blows up as  $\alpha$  approaches 0 or 1.

Let  $x, y \in M$  be given, and choose  $p \in \mathbb{Z}$  so that  $2^p \leq d(x, y) < 2^{p+1}$ . (We may as well assume that  $x \neq y$ .) In order to estimate the sum in (6.13) we consider separately the pieces where  $j \leq p$  or  $j > p$ , and we use (6.4) or (6.5) accordingly. For the first we use (6.4) to obtain that

$$\begin{aligned} \sum_{j \leq p} |f_j(x) - f_j(y)| &\leq \sum_{j \leq p} 2 \sup_M |f_j| \\ &\leq \sum_{j \leq p} k 2^{j\alpha} \\ &\leq C(\alpha) k 2^{p\alpha} \\ &\leq C(\alpha) k d(x, y)^\alpha, \end{aligned} \quad (\text{B.6.14})$$

because of our choice of  $p$ . For the second piece we use (6.5) to get

$$\begin{aligned} \sum_{j > p} |f_j(x) - f_j(y)| &\leq \sum_{j > p} k 2^{j(\alpha-1)} d(x, y) \\ &\leq C(\alpha) k 2^{p(\alpha-1)} d(x, y) \\ &\leq C(\alpha) k d(x, y)^\alpha, \end{aligned} \quad (\text{B.6.15})$$

again using our choice of  $p$ . Lemma 6.12 follows by combining (6.14) and (6.15).

If  $\{f_j\}$  satisfies (6.4), (6.5), and (6.6), then from Lemma 6.12 and (6.6) we can conclude that  $\sum_j f_j(x)$  converges for all  $x \in M$ . To show that the convergence is uniform on compact sets one can make the same kind of analysis as in the proof of Lemma 6.12, but simply taking  $p = 0$ . The point is that the series converge uniformly because they are dominated by geometric series.

This proves the first half of Theorem 6.3. To prove the second half, to represent any Hölder continuous function in this manner, it will be more convenient to establish first another characterization of Hölder continuous functions.

**B.6.16. Theorem:** Let  $(M, d(x, y))$  be a metric space, let  $0 < \alpha < 1$  be given, and let  $g : M \rightarrow \mathbb{R}$  be a real-valued function on  $M$ . Suppose that there exists  $k > 0$  so that for each  $t > 0$  we can find  $g_t : M \rightarrow \mathbb{R}$  such that

$$\sup_M |g - g_t| \leq k t^\alpha \quad \text{and} \quad (B.6.17)$$

$$g_t \text{ is } k t^{\alpha-1}\text{-Lipschitz.} \quad (B.6.18)$$

Then  $g$  is Hölder continuous of order  $\alpha$ . Conversely, if  $g$  is Hölder continuous of order  $\alpha$ , then for each  $t > 0$  there is a function  $g_t : M \rightarrow \mathbb{R}$  which satisfies (6.17) and (6.18), with  $k$  taken to be the Hölder constant of  $g$ .

Again the powers of  $t$  in (6.17) and (6.18) may look a little strange. It would be more standard to try to approximate  $g$  to within an error of  $t$  and then compute what is the right Lipschitz norm. For me it is easier to make the above normalizations because I can remember them better. Roughly speaking,  $g_t$  is the approximation to  $g$  that is smooth at the scale of  $t$ . This idea makes sense no matter what  $\alpha$  is, and then we compute the bounds above in terms of  $\alpha$ .

Let us prove Theorem 6.16. Suppose that  $g$  is given and that  $k$  and  $g_t$  exist as above. Let  $x, y \in M$  be given, and let us estimate  $|g(x) - g(y)|$ . Set  $t = d(x, y)$ . We have that

$$\begin{aligned} |g(x) - g(y)| &\leq |g(x) - g_t(x)| + |g_t(x) - g_t(y)| \\ &\quad + |g_t(y) - g(y)| \\ &\leq k t^\alpha + k t^{\alpha-1} d(x, y) + k t^\alpha \\ &\leq 3k d(x, y)^\alpha. \end{aligned} \quad (B.6.19)$$

Thus  $g$  is Hölder continuous of order  $\alpha$  with constant  $3k$ .

In order to prove the second half of Theorem 6.16 we need a preliminary fact.

**B.6.20. Lemma:** Suppose that  $(M, d(x, y))$  is a metric space and that  $\mathcal{H}$  is a collection of  $L$ -Lipschitz real-valued functions on  $M$  for some number  $L$ . If  $\inf\{h(x) : h \in \mathcal{H}\}$  is finite for some  $x \in M$ , then it is finite for all  $x \in M$ , and the resulting function on  $M$  is  $L$ -Lipschitz.

This is a standard fact. One writes the Lipschitz condition on  $h \in \mathcal{H}$  as

$$h(y) - L d(x, y) \leq h(x) \leq h(y) + L d(x, y) \quad (B.6.21)$$

for all  $x, y \in M$ , and one concludes that

$$\inf_{h \in \mathcal{H}} h(y) - L d(x, y) \leq \inf_{h \in \mathcal{H}} h(x) \leq \inf_{h \in \mathcal{H}} h(y) + L d(x, y). \quad (B.6.22)$$

Lemma 6.20 follows easily from this.

So let us prove now the second half of Theorem 6.16. Let  $g : M \rightarrow \mathbb{R}$  be given and Hölder continuous of order  $\alpha$ . We may as well assume that  $g$  is Hölder continuous with constant  $\leq 1$ , since we can always achieve this normalization by dividing  $g$  by a constant. Let  $t > 0$  be given, and set

$$g_t(x) = \inf\{g(y) + t^{\alpha-1} d(x, y) : y \in M\}. \quad (\text{B.6.23})$$

This is a standard device for approximating functions on a metric space by Lipschitz functions. We view  $g(y) + t^{\alpha-1} d(x, y)$  here as a function of  $x$ , with  $y$  treated as a parameter. As a function of  $x$  is it  $t^{\alpha-1}$ -Lipschitz, because  $d(x, y)$  is 1-Lipschitz as a function of  $x$ , as one can check from the triangle inequality. Lemma 6.20 implies that  $g_t$  is also  $t^{\alpha-1}$ -Lipschitz, at least if we can show that it is finite.

Let us show that we can replace (6.23) by a more localized formula, namely

$$g_t(x) = \inf\{g(y) + t^{\alpha-1} d(x, y) : y \in M, d(x, y) \leq t\}. \quad (\text{B.6.24})$$

Indeed, if  $d(x, y) > t$ , then

$$g(y) + t^{\alpha-1} d(x, y) > g(y) + d(x, y)^\alpha, \quad (\text{B.6.25})$$

since  $\alpha < 1$ . Thus we get that  $g(y) + t^{\alpha-1} d(x, y) > g(x)$  in this case, since we are assuming that  $g$  is Hölder continuous with constant  $\leq 1$ . This means that this  $y$  cannot contribute to the infimum in (6.23), because it gives a larger answer than  $y = x$  does. This proves (6.24).

From (6.24) and the Hölder continuity of  $g$  it follows easily that  $g_t$  is finite, and so  $t^{\alpha-1}$ -Lipschitz, by Lemma 6.20.

It remains to check that (6.17) holds. Notice first that

$$g_t(x) \leq g(x) \quad (\text{B.6.26})$$

for all  $x \in M$ , by the definition (6.23) of  $g_t$  (just take  $y = x$ ). To prove (6.17) it suffices to show that

$$g(x) \leq g_t(x) + t^\alpha \quad (\text{B.6.27})$$

for all  $x \in M$ . This follows from (6.24): given  $y \in M$  with  $d(x, y) \leq t$ , we can use the Hölder condition on  $g$  to get

$$g(x) \leq g(y) + d(x, y)^\alpha \leq g(y) + t^\alpha \leq g(y) + t^{\alpha-1} d(x, y) + t^\alpha. \quad (\text{B.6.28})$$

Taking the infimum over  $y$  we get (6.27). Combining (6.26) with (6.27) we have (6.17), as desired.

This completes the proof of Theorem 6.16. Let us go back now and finish the proof of Theorem 6.3. Let  $f$  be a real-valued function on  $M$  which is Hölder continuous of order  $\alpha$ . Let  $g_t$  be the approximation to  $f$  at the scale of  $t$  provided by the second half of Theorem 6.16 (with  $g = f$ ). Set  $\phi_j = g_{2^{j+1}} - g_{2^j}$ . We would like to use these functions for  $f_j$ , but that does not quite work. They satisfy (6.4) and (6.5) (with  $k$  taken to be a multiple of the Hölder constant for  $f$ ), because of (6.17) and (6.18), but there is a small problem with (6.6). So instead we set

$$f_j(x) = \phi_j(x) - \phi_j(x_0), \quad (\text{B.6.29})$$

where  $x_0 \in M$  is some arbitrarily chosen basepoint. Actually we do this for all but one  $j$ . For one choice  $j_0$  of  $j$  we set

$$f_j(x) = \phi_j(x) - \phi_j(x_0) + f(x_0). \quad (\text{A.6.29}')$$

We choose this  $j_0$  so large so that  $|f(x_0)| \leq 2^{j_0\alpha}$ . This choice ensures that  $f_j$  satisfies (6.4) and (6.5) for all  $j$ , with  $k$  taken to be a multiple of the Hölder constant for  $f$ . (Keep in mind that adding a constant to a function does not affect its Lipschitz constant.)

So with this choice of  $\{f_j\}$  we have (6.4) and (6.5), and we also have (6.6) because  $f_j(x_0) = 0$  for all  $j$  except  $j = j_0$ , for which we have  $f_{j_0}(x_0) = f(x_0)$ . It remains to show that

$$\sum_{j=-\infty}^{\infty} f_j(x) = f(x) \quad (\text{B.6.30})$$

for all  $x \in M$ . Let  $m$  and  $n$  be integers, with  $m \leq j_0 \leq n$ . We have that

$$\sum_{j=m}^n f_j(x) = g_{2^{n+1}}(x) - g_{2^m}(x) - \{g_{2^{n+1}}(x_0) - g_{2^m}(x_0)\} + f(x_0). \quad (\text{B.6.31})$$

The definition of  $g_t$  ensures that

$$\lim_{m \rightarrow -\infty} g_{2^m}(x) - g_{2^m}(x_0) = f(x) - f(x_0). \quad (\text{B.6.32})$$

Specifically, we are using (6.17) here (with  $g = f$ ). Using (6.18) we get that

$$|g_{2^{n+1}}(x) - g_{2^{n+1}}(x_0)| \leq k 2^{(n+1)(\alpha-1)} d(x, x_0). \quad (\text{B.6.33})$$

Since  $\alpha < 1$  we conclude that this tends to 0 as  $n \rightarrow \infty$ . Combining this with (6.31) and (6.32) we obtain (6.30).

This completes the proof of Theorem 6.3.

### B.7. Metric spaces which are doubling.

In the preceding section we saw how one can decompose a Hölder continuous function on a metric space into layers for which the most interesting behavior was concentrated at a given scale. At a fixed scale, however, there was not much to say. In this section we shall assume that the metric space is doubling and try to say more about what happens at fixed scales. (The discussion of hyperbolic geometry in Section 1 is relevant here.)

The first main point will be to construct a suitable partition of unity. To do that we find coverings of  $M$  by balls of a fixed size with controlled overlapping.

Let us assume from now on in this section that  $(M, d(x, y))$  is a metric space which is doubling. Fix a  $t > 0$ .

**B.7.1. Lemma:** *There is a subset  $A = A(t)$  of  $M$  such that*

$$d(x, y) \geq t \quad \text{when } x, y \in A, x \neq y, \tag{B.7.2}$$

and such that  $M \subseteq \bigcup_{x \in A} B(x, t)$ .

We want to  $A$  to be a maximal subset of  $M$  which satisfies (7.2). In order to produce this maximal set we work in bounded subsets initially where any such set must be finite.

Specifically, suppose that  $B$  is a ball in  $M$ , and that  $E$  is a subset of  $B$  which satisfies the analogue of (7.2). Then  $E$  can have at most a bounded number of elements, where the bound depends on  $t$  and the radius of  $B$  but not on  $E$ . Indeed, the doubling condition implies that  $B$  can be covered by a bounded number of balls of radius  $t/2$ , and any such ball can contain at most one element of  $E$ . Therefore  $E$  can contain at most a bounded number of elements.

Fix a sequence of balls  $\{B_j\}$  in  $M$  with  $B_j \subseteq B_{j+1}$  for all  $j$  and  $\bigcup_j B_j = M$ , and let us try to produce a sequence of subsets  $A_j$  of the  $B_j$ 's with the property that  $A_j \supseteq A_{j-1}$  and  $A_j$  is a maximal subset of  $B_j$  which satisfies (7.2). We build these subsets recursively. For  $j = 1$  we take any maximal subset of  $B_1$  which satisfies (7.2). Such a maximal subset exists, since we know that any subset of  $B_1$  which satisfies (7.2) can have only a bounded number of elements. If  $A_j$  has been constructed, then we choose  $A_{j+1}$  to be a maximal subset of  $B_{j+1}$  which contains  $A_j$  and which satisfies (7.2). Again this is possible because of our bound on the number of elements of such a subset. This  $A_{j+1}$  will then be maximal among subsets of  $B_{j+1}$  which satisfy (7.2). (Maximal in the sense that it cannot be made larger,

not that it has the largest possible number of elements.)

Now we can take  $A = \bigcup_j A_j$ , and it is easy to see that  $A$  is a maximal subset of  $M$  which satisfies (7.2). This proves Lemma 7.1.

**B.7.3. Lemma:** *If  $A \subseteq M$  satisfies (7.2) and  $k > 0$  is given, then there is a constant  $C(k)$  so that no point in  $M$  lies in  $B(x, k t)$  for more than  $C(k)$  points  $x \in A$ . Here  $C(k)$  depends also on the doubling constant for  $M$  but not on  $A$  or  $t$ .*

Indeed, let  $p \in M$  be given, and let  $F$  denote the set of  $x \in A$  such that  $p \in B(x, k t)$ . Then  $F \subseteq B(p, k t)$  and  $F$  satisfies (7.2). The doubling condition implies that  $B(p, k t)$  can be covered by  $\leq C(k)$  balls of radius  $t/2$ , and each of these balls cannot contain more than one element of  $F$ . Thus we conclude that  $F$  has at most  $C(k)$  elements, and the lemma follows.

**B.7.4. Lemma (Partition of unity):** *Let  $A$  be as in Lemma 7.1. We can find a family of real-valued functions  $\{\phi_a\}_{a \in A}$  on  $M$  with the following properties:  $0 \leq \phi_a \leq 1$  for all  $a$ ; each  $\phi_a$  is  $C t^{-1}$ -Lipschitz, where the constant  $C$  depends on the doubling constant for  $M$  but nothing else;  $\phi_a(x) = 0$  when  $d(a, x) \geq 2t$ ; and*

$$\sum_{a \in A} \phi_a(x) = 1 \quad (\text{B.7.5})$$

for all  $x \in M$ .

To prove this let us define first some auxiliary bump functions  $\psi_a$  on  $M$ . Let  $f : [0, \infty) \rightarrow [0, 1]$  denote the function which satisfies  $f \equiv 1$  on  $[0, t]$ ,  $f \equiv 0$  on  $[2t, \infty)$ , and  $f$  is linear on  $[t, 2t]$ . Thus  $f$  is  $t^{-1}$ -Lipschitz. Define  $\psi_a : M \rightarrow [0, 1]$  by  $\psi_a(x) = f(d(a, x))$ . Then  $\phi_a$  is  $t^{-1}$ -Lipschitz,  $\psi_a(x) = 0$  when  $d(a, x) \geq 2t$ , and  $\psi_a(x) = 1$  when  $d(x, a) \leq t$ .

Set

$$\phi_a(x) = \frac{\psi_a(x)}{S(x)}, \quad (\text{B.7.6})$$

where  $S(x) = \sum_{b \in A} \psi_b(x)$ . Lemma 7.3 ensures that  $\psi_b(x)$  is nonzero for only a bounded number of  $b$ 's for any given  $x$ , and so this sum is always finite. We have that  $S(x) \geq 1$  for all  $x \in M$ , because  $\bigcup_{p \in A} B(p, t) \supseteq M$ . It is not hard to check that  $S(x)$  is  $C t^{-1}$ -Lipschitz, using the fact that the balls  $B(p, 2t)$ ,  $p \in A$ , have bounded overlap (by Lemma 7.3). That is, given  $x \in M$ ,  $\psi_b(x) \neq 0$  for only a bounded number of  $b \in A$ , and we can use the fact that each  $\psi_b$  is  $t^{-1}$ -Lipschitz to get a similar bound for  $S(x)$ . Once we have this bound for  $S(x)$  we can easily conclude that each  $\phi_a$  is  $C t^{-1}$ -Lipschitz for a suitable constant  $C$ . That  $0 \leq \phi_a \leq 1$  follows from

the same property of  $\psi_a$  and the fact that  $S \geq 1$  everywhere.  $\phi_a(x) = 0$  when  $d(a, x) \geq 2t$  also follows from the corresponding property of  $\psi_a$ . The identity (7.5) is an immediate consequence of (7.6).

This completes the proof of Lemma 7.4.

The partition of unity in Lemma 7.4 permits us to define a linear operator for approximating Hölder continuous functions by Lipschitz functions. (Compare with the nonlinear procedure in (6.23).) Let  $A$ ,  $\{\phi_a\}$  be as in Lemma 7.4, and define an operator  $E_t$  acting on functions on  $M$  by

$$E_t(f)(x) = \sum_{a \in A} f(a)\phi_a(x). \quad (\text{B.7.7})$$

**B.7.8. Lemma:** *There is a constant  $C$ , depending only on the doubling constant of  $M$ , so that*

$$\sup_M |f - E_t(f)| \leq C k t^\alpha \quad (\text{B.7.9})$$

whenever  $f : M \rightarrow \mathbb{R}$  is Hölder continuous of order  $\alpha$  and with constant  $k$ .

Indeed,

$$f(x) - E_t(f)(x) = \sum_{a \in A} (f(x) - f(a))\phi_a(x), \quad (\text{B.7.10})$$

because of (7.5) and (7.7). If  $\phi_a(x) \neq 0$ , then  $x \in B(a, 2t)$ , and this can happen for only a bounded number of  $a$ 's, by Lemma 7.3. For each of these  $a$ 's we have that  $|f(x) - f(a)| \leq k d(x, a)^\alpha \leq k (2t)^\alpha$ . From this we get that  $|f(x) - f(a)| \leq C k t^\alpha$ , and (7.9) follows since  $x \in M$  is arbitrary. This proves Lemma 7.8.

**B.7.11. Lemma:** *There is a constant  $C$ , depending only on the doubling constant of  $M$ , so that  $E_t(f)$  is  $C k t^{\alpha-1}$ -Lipschitz when  $f : M \rightarrow \mathbb{R}$  is Hölder continuous of order  $\alpha$  and with constant  $k$ .*

Let  $x, y \in M$  be given, and let us estimate  $|E_t(f)(x) - E_t(f)(y)|$ . Suppose first that  $d(x, y) \geq t$ . In this case we have that

$$\begin{aligned} |E_t(f)(x) - E_t(f)(y)| &\leq |E_t(f)(x) - f(x)| + |f(x) - f(y)| \\ &\quad + |f(y) - E_t(f)(y)| \\ &\leq C k t^\alpha + k d(x, y)^\alpha + C k t^\alpha \quad (\text{B.7.12}) \\ &\leq C k t^{\alpha-1} d(x, y), \end{aligned}$$

since  $d(x, y) \geq t$ . This is the estimate that we want. If  $d(x, y) \leq t$ , then we compute as follows:

$$\begin{aligned} E_t(f)(x) - E_t(f)(y) &= \sum_{a \in A} f(a) (\phi_a(x) - \phi_a(y)) \\ &= \sum_{a \in A} (f(a) - f(x)) (\phi_a(x) - \phi_a(y)). \end{aligned} \quad (\text{B.7.13})$$

For this last equality we have used the observation that  $\sum_{a \in A} (\phi_a(x) - \phi_a(y)) = 0$ , because of (7.5). If  $\phi_a(x) \neq 0$ , then  $x \in B(a, 2t)$ , and this can happen for only a bounded number of  $a$ 's. If  $\phi_a(y) \neq 0$ , then  $y \in B(a, 2t)$ , and this can happen for only a bounded number of  $a$ 's as well. In this case  $x \in B(a, 3t)$ , since we are assuming that  $d(x, y) \leq t$ . In either event we have that  $x \in B(a, 3t)$  and so  $|f(a) - f(x)| \leq k(3t)^\alpha$ . We also have that  $|\phi_a(x) - \phi_a(y)| \leq t^{-1} d(x, y)$ . Altogether we get then that

$$|E_t(f)(x) - E_t(f)(y)| \leq C k t^\alpha t^{-1} d(x, y), \quad (\text{B.7.14})$$

which is the estimate that we wanted. This completes the proof of Lemma 7.11.

Lemmas 7.8 and 7.11 provide a new proof of the second half of Theorem 6.16. This new proof has the disadvantage that it requires the additional assumption that  $M$  be doubling, but it has the advantage of providing a construction for the Lipschitz approximations that one can understand with one's eyes. This leads also to another proof of the second half of Theorem 6.3 in the case of doubling spaces in which we can control the form of the functions  $f_j$  much better.

This type of analysis has a consequence for the first half of Theorem 6.3 also. Let us write  $A(2^j)$  for  $A = A(t)$  with  $t = 2^j$ , and let us write  $\phi_{j,a}$ ,  $a \in A(2^j)$ , for the functions provided by Lemma 7.4, with  $t = 2^j$ . Fix some basepoint  $x_0 \in M$ , and set

$$\theta_{j,a}(x) = \phi_{j,a}(x) - \phi_{j,a}(x_0). \quad (\text{B.7.15})$$

**B.7.16. Lemma:** *Notations and assumptions as above. Let  $\lambda_{j,a}$ ,  $j \in \mathbb{Z}$ ,  $a \in A(2^j)$ , be a uniformly bounded collection of real numbers, and let  $0 < \alpha < 1$  be given. Then*

$$\sum_{j \in \mathbb{Z}} \sum_{a \in A(2^j)} \lambda_{j,a} 2^{j\alpha} \theta_{j,a}(x) \quad (\text{B.7.17})$$

*converges for every  $x \in M$ , and the limit defines a Hölder continuous function on  $M$  of order  $\alpha$ .*

The point here is that we get a Hölder continuous function for any choice of  $\{\lambda_{j,a}\}$  whatsoever, so long as it is bounded. We shall discuss this further in a moment.

The double sum in (7.17) actually converges absolutely, but one can interpret it as a sum first in  $a$ , in which all but finitely many terms vanish, and then a sum in  $j$ .

To prove the lemma we set  $f_j(x) = \sum_{a \in A(2^j)} \lambda_{j,a} 2^{j\alpha} \theta_{j,a}(x)$ , and we try to apply Theorem 6.3. We have that  $\theta_{j,a}(x_0) = 0$  for all  $j$  and  $a$ , and so  $f_j(x_0) = 0$  for all  $j$ , and so (6.6) follows. Let us check (6.4). If  $\theta_{j,a}(x) \neq 0$ , then either  $x \in B(a, 2t)$  or  $x_0 \in B(a, 2t)$ , and in either case this can happen for only a bounded number of  $a$ 's. Since  $\phi_{j,a}$  takes values in  $[0, 1]$  we have that  $\theta_{j,a}$  takes values in  $[-1, 1]$ , and we conclude that each  $\lambda_{j,a} 2^{j\alpha} \theta_{j,a}(x)$  is bounded by a constant times  $2^{j\alpha}$ . Since the number of nonzero terms is bounded we get (6.4).

Now let us check (6.5). Let  $x, y \in M$  be given, and let us estimate  $|f_j(x) - f_j(y)|$ . Notice that  $\theta_{j,a}(x) - \theta_{j,a}(y) = \phi_{j,a}(x) - \phi_{j,a}(y)$ , and that this quantity is nonzero for only a bounded number of  $a$ 's again. When it is nonzero it is bounded by  $C 2^{-j} d(x, y)$ , by Lemma 7.4. Thus we conclude that  $|f_j(x) - f_j(y)|$  is bounded by  $C 2^{j\alpha} 2^{-j} d(x, y)$ , and this implies the Lipschitz condition (6.5).

Theorem 6.3 implies now that  $\sum_j f_j(x)$  converges for every  $x \in M$  and defines a Hölder continuous function on  $M$  of order  $\alpha$ . This proves Lemma 7.16.

Note that the precise form of the  $\phi_{a,j}$ 's does not matter for Lemma 7.16, just the basic properties of their size, support, and Lipschitz norms. We do not need the identity (7.5).

What does Lemma 7.16 mean? Do not take its precise form too seriously, the point is more the general type of construction that it permits us to make. It tells us that we can build Hölder continuous functions with approximately prescribed behavior at each individual scale and location. Think of  $\theta_{j,a}$  as being some kind of bump function that lives near  $a \in A(2^j)$  and which lives at the scale of  $2^j$ . It is not quite fair to say that  $\theta_{j,a}$  lives near  $a$ ; although  $\phi_{j,a}$  is supported in  $B(a, 2t)$ , this need not be true of  $\theta_{j,a}$ , because of its definition (7.15). However, the only disturbance to this statement is the additive constant  $-\phi_{j,a}(x_0)$ , which plays only a minor technical role. This bump function is not normalized to have bounded Hölder constant for the exponent  $\alpha$ , but  $2^{ja} \theta_{j,a}$  is properly normalized. Thus Lemma 7.16 permits us to combine these normalized bumps in an arbitrary manner so long as we give them bounded coefficients. This is somewhat remarkable, even if it is not very difficult to prove. It says that the various scales and locations are approximately independent of each other for Hölder continu-

ous functions. In the previous section we saw that the different scales were independent of each other, and now we are using the doubling condition to make both scales and locations independent of each other.

### B.8. Spaces of homogeneous type.

A *space of homogeneous type* is a metric space  $(M, d(x, y))$  equipped with a doubling measure  $\mu$ . Actually, let us require only that  $d(x, y)$  be a quasimetric, but to extend Definition 3.1 (doubling measures) to this case one has to be a little careful because the balls for quasimetrics need not be measurable. It is easy enough to avoid this technicality in formulating the notion of doubling measure ((3.3) is helpful in this regard), but instead we simply restrict ourselves to quasimetrics for which open balls are Borel sets. Quasimetrics which are powers of metrics, as in (2.2), always enjoy this property.

Actually, we should also ask that  $\mu$  be Borel regular, so that one has the usual compatibility between topology and measure. It suffices to ask that  $M$  be complete, because then closed and bounded subsets of  $M$  are compact, open subsets are  $\sigma$ -compact, and we can apply Theorem 2.18 in [Rudin].

Spaces of homogeneous type are very useful in analysis, because they provide a general setting where certain types of arguments work. The basic references are [Coif–Weis]<sub>AH</sub>, [Coif–Weis]<sub>HS</sub>, see also [Stein]<sub>HA</sub>. ([Coif–Weis]<sub>HS</sub> has a very nice discussion of examples.)

Let us discuss examples for a moment. We can easily get some by remembering the discussion of Ahlfors regular spaces in Section 3 and realizing that they are all examples of spaces of homogeneous type. To appreciate these examples one should think a little about their setting in analysis. Euclidean spaces equipped with Lebesgue measure are spaces of homogeneous type, and this corresponds to “standard” analysis.  $\mathbb{R}^{n+1}$  equipped with the parabolic metric (2.9) and Lebesgue measure is also a space of homogeneous type, and it corresponds to analysis of the heat equation (instead of the Laplacian). The Heisenberg group  $H_n$  with the metric discussed in Section 2 and Lebesgue measure is another space of homogeneous type, and the natural analysis on it arises in several complex variables. Our symbolic Cantor sets  $F^\infty$  from Section 2 can also be made into spaces of homogeneous type, and analysis on them can be viewed in terms of martingales in probability theory.

So what kind of analysis can we do on a space of homogeneous type  $(M, d(x, y), \mu)$ ? Here is the simplest example. Suppose that  $f \in L^1_{loc}(M, \mu)$ .

Then  $\mu$ -almost every element of  $M$  is a Lebesgue point of  $f$ , i.e.,

$$\lim_{r \rightarrow 0} \frac{1}{\mu(B(x, r))} \int_{B(x, r)} |f(y) - f(x)| d\mu(y) = 0 \quad (\text{B.8.1})$$

for almost every  $x$ . The main point of the proof is that standard arguments for proving this result on Euclidean spaces (involving covering lemmas) extend to this setting. (See Section 34.)

This example is very nice because it illustrates a basic point: a lot of classical analysis on Euclidean spaces does not make sense simply for measure spaces, or simply for metric spaces, but in the presence of both structures one can at least formulate certain concepts, like the concept of a Lebesgue point. The notion of spaces of homogeneous type imposes a mild compatibility between measure and metric which is adequate to prove a lot of theorems. In particular it is sufficient to get a lot of mileage out of covering lemmas.

What other kinds of analysis work on spaces of homogeneous type? We shall give some precise examples in the next three sections, but for the moment let us take a brief look at singular integral operators. I do not want to get into a serious discussion of singular integral operators, but to illustrate the concept consider the following. Let  $\Delta$  denote the Laplace operator on  $\mathbb{R}^n$ , which is given by

$$\Delta = \frac{\partial^2}{\partial x_1^2} + \cdots + \frac{\partial^2}{\partial x_n^2}. \quad (\text{B.8.2})$$

If  $g(x)$  is a smooth function with compact support on  $\mathbb{R}^n$ , then all of the second partial derivatives of  $g$  can be recovered from  $\Delta g$  through singular integral operators. Indeed, as is well known, we have that

$$g(x) = c_n \int_{\mathbb{R}^n} \frac{1}{|x - y|^{n-2}} \Delta g(y) dy \quad (\text{B.8.3})$$

when  $n \neq 2$ , where  $c_n$  is some constant, and there is an analogous formula using  $\log|x - y|$  when  $n = 2$ . If  $n \geq 2$ ,  $1 \leq i, j \leq n$ , and  $i \neq j$  (for instance), then

$$\frac{\partial^2}{\partial x_i \partial x_j} g(x) = c'_n \text{ P.V.} \int_{\mathbb{R}^n} \frac{(x_i - y_i)(x_j - y_j)}{|x - y|^{n+2}} \Delta g(y) dy, \quad (\text{B.8.4})$$

where the integral on the right side should be interpreted as a Cauchy principal value.

This is a basic example of a singular integral operator on  $\mathbb{R}^n$ , viewed here as an operator acting on  $\Delta g$  and giving  $\frac{\partial^2}{\partial x_i \partial x_j} g$ . It is not hard to show

that such an operator is bounded on  $L^2(\mathbb{R}^n)$ , but it is in fact bounded on  $L^p$  when  $1 < p < \infty$ , and not when  $p = 1, \infty$ . ( $L^2$  is always special because of the Hilbert space structure, the Fourier transform, etc. To go to  $L^p$  spaces in this context one has to come to terms with some geometry.) These operators are subtle because they cannot be analyzed successfully just in terms of the size of their kernels, one has to take into account the cancellations as well. See [Stein]SI.

There are analogues of these operators on  $\mathbb{R}^{n+1}$  associated to the heat operator instead of the Laplacian, for which the parabolic metric defines the right geometry. There are also analogous operators on the Heisenberg group using the natural “sub-Laplacian” there. On our symbolic Cantor set  $F^\infty$  there does not seem to be a nice version of  $\frac{\partial}{\partial x}$ , but there are still operators of this general type, martingale transforms.

These specific operators do not have an abstract form on spaces of homogeneous type, but there are natural classes of singular integral operators which include these examples and which can be defined on spaces of homogeneous type. This was one of the main motivations behind the concept, the study of singular integral operators in a general setting.

Note however that it is not so easy to define specific interesting operators on a general space of homogeneous type. In practice the interesting operators come from the particular space, and the general theory simply applies to the whole class of operators without distinguishing certain ones.

### B.9. Hölder continuity and mean oscillation.

Let  $(M, d(x, y), \mu)$  be a space of homogeneous type, and  $g \in L^1_{loc}(M, \mu)$  be given. Set

$$\text{mo}(x, r) = \frac{1}{\mu(B(x, r))} \int_{B(x, r)} |g(y) - \text{m}_{x, r} g| d\mu(y), \quad (\text{B.9.1})$$

where

$$\text{m}_{x, r} g = \frac{1}{\mu(B(x, r))} \int_{B(x, r)} g(z) d\mu(z). \quad (\text{B.9.2})$$

$\text{mo}(x, r)$  is the *mean oscillation* of  $g$  over the ball  $B(x, r)$ , the average amount by which  $g$  deviates from its average on that ball. One can think of it as a way to measure a snapshot of  $g$ . In this section and the next two we want to look at how the mean oscillation controls the behavior of  $g$ . (For notational simplicity we do not make the dependence of  $\text{mo}(x, r)$  on  $g$  explicit, but it should always be clear from the context.)

**B.9.3. Proposition:** *Notation and assumptions as above. Assume that  $\alpha > 0$  and that there is a constant  $k > 0$  so that*

$$\text{mo}(x, r) \leq k r^\alpha \quad (\text{B.9.4})$$

for all  $x \in M$  and  $r > 0$ . Then  $g$  can be modified on a set of  $\mu$ -measure zero to get a Hölder continuous function of order  $\alpha$ .

Note that the converse is true, and easy to derive from the definitions.

Let us prove the proposition. As mentioned in the previous section almost every point in  $M$  is a Lebesgue point for  $g$ . Let us show that

$$|g(x) - g(y)| \leq C k d(x, y)^\alpha \quad (\text{B.9.5})$$

when  $x$  and  $y$  are Lebesgue points of  $g$ , with a constant  $C$  that does not depend on  $x$  or  $y$ .

Notice that

$$|\text{m}_{z,t} g - \text{m}_{z,2t} g| \leq C \text{mo}(z, 2t) \quad (\text{B.9.6})$$

for all  $z \in M$  and  $t > 0$ . This is not hard to check, using the doubling condition for  $\mu$ . From (9.4) we get that

$$|\text{m}_{z,t} g - \text{m}_{z,2t} g| \leq C k t^\alpha. \quad (\text{B.9.7})$$

Since  $x$  is a Lebesgue point for  $g$  we have that

$$\lim_{t \rightarrow 0} \text{m}_{x,t} g = g(x), \quad (\text{B.9.8})$$

and similarly for  $y$ . This is all that we really need to know about  $x$  and  $y$ . If  $r > 0$ , then we obtain that

$$\text{m}_{x,r} g - g(x) = \sum_{j=0}^{\infty} (\text{m}_{x,2^{-j}r} g - \text{m}_{x,2^{-j-1}r} g). \quad (\text{B.9.9})$$

Hence

$$|g(x) - \text{m}_{x,r} g| \leq \sum_{j=0}^{\infty} C k (2^{-j} r)^\alpha \leq C k r^\alpha. \quad (\text{B.9.10})$$

Notice that this last constant  $C$  depends on  $\alpha$  (and blows up as  $\alpha \rightarrow 0$ ).

Set  $r = d(x, y)$ . Since  $d(x, y)$  is a quasimetric we have  $B(x, r) \cup B(y, r) \subseteq B(x, Lr)$  for some constant  $L$  which does not depend on  $x$  or  $y$ . (If  $d(x, y)$  is a metric then we can take  $L = 2$ .) We have that

$$|\text{m}_{x,r} g - \text{m}_{y,r} g| \leq |\text{m}_{x,r} g - \text{m}_{x,Lr} g| + |\text{m}_{x,Lr} g - \text{m}_{y,r} g| \leq C \text{mo}(x, Lr). \quad (\text{B.9.11})$$

This can be derived from the definitions, using the doubling condition, as in (9.6). We conclude that

$$|\mathbf{m}_{x,r} g - \mathbf{m}_{y,r} g| \leq C k r^\alpha. \quad (\text{B.9.12})$$

Altogether we obtain that

$$|g(x) - g(y)| \leq |g(x) - \mathbf{m}_{x,r} g| + |\mathbf{m}_{x,r} g - \mathbf{m}_{y,r} g| + |\mathbf{m}_{y,r} g - g(y)| \leq C k r^\alpha, \quad (\text{B.9.13})$$

because of (9.10), (9.12), and the analogue of (9.10) for  $y$  instead of  $x$ . This proves (9.5), and Proposition 9.3 follows.

In short Proposition 9.3 implies that good bounds on the mean oscillation of  $g$  imply good bounds on the maximal oscillation of  $g$ . In geometry one can sometimes control the mean oscillation using isoperimetric inequalities.

### B.10. Vanishing mean oscillation.

Let  $(M, d(x, y), \mu)$  be a space of homogeneous type. Let  $V$  denote the space of locally integrable functions  $g$  on  $M$  such that

$$\lim_{r \rightarrow 0} \sup_{x \in M} \text{mo}(x, r) = 0, \quad (\text{B.10.1})$$

where  $\text{mo}(x, r)$  is as in (9.1). This is a trivial variation on the concept of *vanishing mean oscillation*, but the precise choice of definition is slightly different from the norm, and so we use the nonstandard notation  $V$  to denote the space of these functions.

The idea is that we measure an approximate continuity using mean oscillation instead of maximal oscillation. If we replaced the average in (9.1) with a supremum, then (10.1) would reduce to the requirement that  $g$  be uniformly continuous.

Are there nontrivial examples of functions in  $V$ ? On the real line, with the usual metric and Lebesgue measure, the functions  $|\log|x||^s$  lie in  $V$  for any  $0 < s < 1$ . If one wants bounded examples, one can take the cosine of these functions. Thus Proposition 9.3 does not work in this context. One can see this in the proof, in the importance of  $\alpha$  being positive in the summing of the geometric series in (9.10).

Thus functions in  $V$  do not have to be continuous, even after correcting their values on a set of measure zero. Still they do enjoy some residual continuity properties, some aspects of which we shall describe now. Note that functions which lie in the critical Sobolev spaces, the Sobolev spaces that just miss being contained in the space of continuous functions, are contained in  $V$ . (See also the next section.)

**B.10.2. Lemma:** Suppose that  $(M, d(x, y), \mu)$  is a space of homogeneous type, and let  $g$  be a function in  $V$ . Then for each  $t > 0$  we can find a continuous function  $g_t$  on  $M$  such that

$$\lim_{t \rightarrow 0} \sup\{|g_t(x) - g_t(y)| : x, y \in M, d(x, y) \leq t\} = 0, \quad (\text{B.10.3})$$

and

$$\lim_{t \rightarrow 0} \sup_{x \in M} \frac{1}{\mu(B(x, t))} \int_{B(x, t)} |g(y) - g_t(y)| d\mu(y) = 0. \quad (\text{B.10.4})$$

The first condition says that  $g_t$  is almost constant at the scale of  $t$  when  $t$  is small, and the second condition says that  $g_t$  approximates  $g$  very well on average at the scale of  $t$ .

Before we prove this let us record a corresponding “uniqueness” result.

**B.10.5. Lemma:** Notations and assumptions as in Lemma 10.3. If  $h_t$  is another family of functions on  $M$  that satisfy (10.3) and (10.4) with  $g_t$  replaced with  $h_t$ , then

$$\lim_{t \rightarrow 0} \sup_M |g_t - h_t| = 0. \quad (\text{B.10.6})$$

Thus a function in  $V$  has an almost canonical family of continuous approximations.

Lemma 10.5 is easy to verify and we leave the details to the reader. The main point is that  $g_t(x)$  and  $h_t(x)$  are both very well approximated by the average of  $g$  over  $B(x, t)$  when  $t$  is small, because of (10.3) and (10.4).

Now let us prove Lemma 10.2. We first reduce to the case where  $d(x, y)$  is a metric instead of a quasimetric. We can do this because of (2.2). It is a little easier to do this in two steps, to first reduce to the case where  $d(x, y)$  is a power of a metric, and then to get rid of the power. The point is that if we change  $d(x, y)$  by a power, or we change it to something of the same size, then the requirements on  $g_t$  are not really changed, it is just a question of relabelling the  $t$ 's. Actually there is also a small matter of using the doubling property for  $\mu$  so as not to disturb (10.4) too much when we replace  $d(x, y)$  by something which is merely of the same size.

Thus we may assume that  $d(x, y)$  is actually a metric.

Fix  $t > 0$ , and let  $A \subseteq M$  and  $\{\phi_a\}_{a \in A}$  be as in Lemmas 7.1 and 7.4. (Remember Lemma 3.4, which ensures that  $(M, d(x, y))$  is doubling as a metric space.) Define  $g_t$  by

$$g_t(x) = \sum_{a \in A} (m_{a,t} g) \phi_a(x), \quad (\text{B.10.7})$$

where  $m_{a,t}g$  is defined as in (9.2). This is just the obvious way to try to build a continuous function using partitions of unity whose value at a point  $x$  is approximately the average of  $g$  over  $B(x, t)$ .

Let us check (10.3) and (10.4). Let  $x, y \in M$  be given, with  $d(x, y) \leq t$ . We have that

$$g_t(x) - g_t(y) = \sum_{a \in A} m_{a,t}g(\phi_a(x) - \phi_a(y)). \quad (\text{B.10.8})$$

Using (7.5) we can convert this into

$$g_t(x) - g_t(y) = \sum_{a \in A} (m_{a,t}g - m_{x,t}g)(\phi_a(x) - \phi_a(y)). \quad (\text{B.10.9})$$

If  $\phi_a(x) \neq 0$ , then  $x \in B(a, 2t)$ , because of Lemma 7.4. Similarly  $y \in B(a, 2t)$  if  $\phi_a(y) \neq 0$ , and in either case we get that  $d(a, x) \leq 3t$ . These are the only  $a$ 's which are relevant for (10.8), and there is only a bounded number of them, because of Lemma 7.3. Therefore

$$|g_t(x) - g_t(y)| \leq C \sup\{|m_{a,t}g - m_{x,t}g| : a \in A, d(a, x) \leq 3t\}. \quad (\text{B.10.10})$$

On the other hand

$$|m_{a,t}g - m_{x,t}g| \leq C \text{mo}(x, 4t) \quad (\text{B.10.11})$$

when  $d(a, x) \leq 3t$ . This can be computed from the definitions, as in (9.11). Combining this with (10.10) we can obtain (10.3) from the assumption that  $g$  lies in  $V$ .

This leaves (10.4), which is similar. Notice first that

$$g(y) - g_t(y) = \sum_{a \in A} (g(y) - m_{a,t}g) \phi_a(y), \quad (\text{B.10.12})$$

because of (10.7) and (7.5). Thus

$$\begin{aligned} & \frac{1}{\mu(B(x,t))} \int_{B(x,t)} |g(y) - g_t(y)| d\mu(y) \\ & \leq \sum_{a \in A} \frac{1}{\mu(B(x,t))} \int_{B(x,t)} |g(y) - m_{a,t}g| \phi_a(y) d\mu(y). \end{aligned} \quad (\text{B.10.13})$$

In order for a term in the sum on the right to be nonzero we must have that  $\phi_a$  does not vanish identically on  $B(x, t)$ , which means that there must be a point  $y \in B(x, t)$  such that  $y \in B(a, 2t)$ . This means that  $x \in B(a, 3t)$ , and this can happen only for a bounded number of  $a \in A$ , because of Lemma 7.3. For each of these  $a$ 's we have that

$$\frac{1}{\mu(B(x,t))} \int_{B(x,t)} |g(y) - m_{a,t}g| d\mu(y) \leq C \text{mo}(x, 4t). \quad (\text{B.10.14})$$

This last inequality is another variant of (9.11), and it can be derived from the definition (9.1) of  $\text{mo}(x, 4t)$  and the doubling condition on  $\mu$ . Once we have (10.14) we can derive (10.4) from (10.13) and the assumption that  $g \in V$ .

This completes the proof of Lemma 10.2.

The preceding argument also works when  $g$  takes values in some  $\mathbb{R}^n$ , or even in a Banach space. This observation is potentially useful because in some cases one wants  $g$  really to take values in some special set, like a manifold, or a metric space. From (10.3) and (10.4) we have that the approximations  $g_t$  take values very close to the same set, at least when  $t$  is small enough. If the range of  $g$  is a nice set, like a finite polyhedron or a manifold, then we can probably deform the  $g_t$ 's slightly so as to take values in the same set. Under suitable conditions we can also get these approximations to be homotopic to each other, at least for small  $t$ . This would use also the uniqueness result Lemma 10.5.

The point of all of this is that one can normally extract from mappings with vanishing mean oscillation practically the same kind of topological information as for continuous mappings. I first encountered this idea in [Doug], specifically Theorem 7.36 on p.189 of [Doug]. This result gave the index of a Toeplitz operator as the winding number of its functional symbol, but where the latter was not continuous so that the concept of the winding number required interpretation. Vanishing mean oscillation was not mentioned in [Doug] in part because the definition had not yet been introduced by Sarason [Sar]. Actually in this setting of complex analysis and operator theory a different description of the function spaces arose naturally, and the connection with the real-variable notion of vanishing mean oscillation was made through the celebrated duality theorem of Fefferman (as discussed in [Sar]). For the purpose of extracting topological information however it is only the real-variable aspects that matter. See [Brez–Nir] for more information about topological properties of mappings with vanishing mean oscillation, especially degree theory.

In trying to understand the computations of this section one should think back to the examples of  $|\log|x||^s$  and its cosine as functions on the real line which lie in  $V$ . These functions are not continuous, or even bounded in the first case. Lemma 10.2 provides a certain family of approximations to these functions. As  $t$  moves these approximations move slowly, because of the uniqueness result Lemma 10.5 (which implies that  $g_t$  is very close to  $g_{2t}$  when  $t$  is small, for instance). As  $t$  goes down to 0 these approximations can spin around an infinite amount, that is what happens in these unbounded and discontinuous examples, but the spinning is slow, and the approximations are almost canonical.

### B.11. Bounded mean oscillation.

Let  $(M, d(x, y), \mu)$  be a space of homogeneous type. Let  $BMO$  (“bounded mean oscillation”) denote the space of locally integrable functions  $g$  on  $M$  which satisfy the condition

$$\|g\|_* = \sup\{\text{mo}(x, r) : x \in M, r > 0\} < \infty, \quad (\text{B.11.1})$$

where  $\text{mo}(x, r)$  is as in (9.1).

This definition may seem strange, but it shows up naturally in many problems, as we shall see later.

Every bounded function on  $M$  satisfies this condition. The function  $\log|x|$  on  $\mathbb{R}$  also lies in  $BMO$ . This is the most basic example of an unbounded  $BMO$  function.

Roughly speaking,  $BMO$  is to bounded functions as the space  $V$  in the previous section is to uniformly continuous functions.

Note that (11.1) is not affected if we add a constant to  $g$ . This is a quietly crucial point. If we drop “oscillation” from  $BMO$ , and require instead that

$$\sup_{x,r} \frac{1}{\mu(B(x, r))} \int_{B(x, r)} |g(y)| d\mu(y) < \infty, \quad (\text{B.11.2})$$

then we would simply recover  $L^\infty$ . By permitting the averages to be unbounded while keeping bounded the mean oscillation we get new functions like the logarithm.

Notice also that (11.1) scales in the same way as the  $L^\infty$  norm. If we are working on  $\mathbb{R}^n$ , for instance, and  $a > 0$  is given, then  $\|g(x)\|_* = \|g(ax)\|_*$ , just as they have also the same  $L^\infty$  norm. In practice, if one has a situation where the scaling is the same as for  $L^\infty$ , but constants can be added without affecting anything, then there is a good chance that  $BMO$  is natural.

Here is an example. Let  $g$  be a function on  $\mathbb{R}^n$  such that  $\nabla g \in L^n$ . What can we say about  $g$ ? We can assume that  $\nabla g$  is taken in the sense of distributions, or we can assume that  $g$  is actually smooth and look for a priori estimates. Observe that

$$\int_{\mathbb{R}^n} |\nabla g(x)|^n dx \quad (\text{B.11.3})$$

scales in the same manner as the  $L^\infty$  norm, i.e., (11.3) does not change if we replace  $g(x)$  with  $g(ax)$ . Also (11.3) does not change if we add a constant to  $g$ . The aforementioned principle suggests that  $BMO$  should be relevant for this situation. When  $n = 1$  this is not really true; we can use

the fundamental theorem of calculus to say that  $\nabla g \in L^1(\mathbb{R})$  implies that  $g$  is bounded, and that the difference between the supremum and infimum of  $g$  is controlled by (11.3). When  $n > 1$  this is no longer true, and this is the well-known failure of the Sobolev embedding at the critical exponent. We do have in this case that

$$\|g\|_* \leq C \left( \int_{\mathbb{R}^n} |\nabla g(x)|^n dx \right)^{\frac{1}{n}}. \quad (\text{B.11.4})$$

This is a standard consequence of the Poincaré inequality, and one can also show that  $g$  lies in the space  $V$  of the preceding section when  $\nabla g \in L^n(\mathbb{R})$  in the sense of distributions. There are more refined versions of these results, but one cannot get away from the fact that the right hand side can be finite for unbounded functions.

For the sake of comparison, recall the Sobolev inequalities

$$\left( \int_{\mathbb{R}^n} |g(x)|^q dx \right)^{\frac{1}{q}} \leq C(p, n) \left( \int_{\mathbb{R}^n} |\nabla g(x)|^p dx \right)^{\frac{1}{p}}, \quad (\text{B.11.5})$$

where  $1/q = 1/p - 1/n$  and  $1 \leq p < n$ . For this we need to add an assumption about  $g$ , that it has compact support for instance, but the bound does not depend on this assumption in a quantitative way. As  $p \rightarrow n$  we have  $q \rightarrow \infty$ , but when  $n > 1$  the estimate degenerates unless we switch to  $BMO$ .

It is often the case in analysis that functions are not bounded when one would like them to be, but that they do lie in  $BMO$ . Another example of this phenomenon is provided by the fact that standard singular integral operators as mentioned in Section 8 are not bounded on  $L^\infty$  but do map  $L^\infty$  into  $BMO$ , and even  $BMO$  into itself under suitable conditions. (See [Garn], [Jour], [Stein]<sub>HA</sub>.)

How close are  $BMO$  functions to being bounded? A famous theorem of John and Nirenberg (see [Garn], [Jour], [Stein]<sub>HA</sub>) says that a  $BMO$  function on  $\mathbb{R}^n$  lies in  $L_{loc}^p$  for all  $p < \infty$ . In fact one can define  $BMO$  in terms of an  $L^p$  norm in the mean oscillation  $mo(x, r)$  from (9.1) and get an equivalent condition.  $BMO$  functions are even exponentially integrable, and one can define  $BMO$  in terms of exponential integrals. The logarithm provides the “worst” degree of unboundedness that  $BMO$  functions can have.

These facts work not only on Euclidean spaces but on any space of homogeneous type. This provides another example of how spaces of homogeneous type have the right amount of geometry for doing certain kinds of analysis. This is a point worthy of reflection: one can talk about  $L^p$  spaces

on measure spaces, one can talk about continuous functions and Lipschitz functions and so forth on metric spaces, but to define  $BMO$  we need some of each.

Nice theorem of Strömberg (see [Garn], [Jour], [Stein]<sub>HA</sub>):  $g$  lies in  $BMO$  means that for each ball  $B$  in  $M$  there is some real number so that at 90% of the points in  $B$   $g(x)$  differs from that number by a bounded amount. (The “bounded amount” is not permitted to depend on  $B$ , but the “number” is.) This captures well a basic idea of  $BMO$ , and of harmonic analysis in general, that it is often natural to say that something behaves well only at most places, and not everywhere, and that if such a thing is true uniformly at all scales and locations, then one can often derive information that appears at first to be much stronger than what one started with.

General references for  $BMO$  include [Garn], [Jour], [Stein]<sub>HA</sub>. We shall return to the John-Nirenberg theorem in Section 40. Another kind of bound on the oscillations of  $BMO$  functions is given in Lemma 42.1.

### III. Rigidity and structure

#### B.12. Differentiability almost everywhere.

**B.12.1. Theorem:** *If  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is Lipschitz, then  $f$  is differentiable at (Lebesgue) almost all points in  $\mathbb{R}^n$ .*

This is a fantastic theorem. A proof is described in Section 35 below. See also [Fed]<sub>GMT</sub>, [Stein]<sub>SI</sub>.

Let us think about Lipschitz mappings in terms of snapshots. Given  $f : \mathbb{R}^n \rightarrow \mathbb{R}$ ,  $x \in \mathbb{R}^n$ , and  $r > 0$ , define  $f_{x,r} : B(0,1) \rightarrow \mathbb{R}$  by

$$f_{x,r}(h) = \frac{f(x + r h) - f(x)}{r}. \quad (\text{B.12.2})$$

The Lipschitz condition says exactly that the family of functions  $f_{x,r}$ ,  $x \in \mathbb{R}^n$ ,  $r > 0$ , is uniformly bounded. Theorem 12.1 says that for almost all  $x \in \mathbb{R}^n$  we have that  $f_{x,r}$  converges uniformly on  $B(0,1)$  as  $r \rightarrow 0$  to a linear function. Thus we can progress from boundedness to the existence of a limit, at almost all points anyway.

This is fantastic. It is a rigidity statement that is not incorporated explicitly into the definition (unlike smoothness). The potential limit is not known in advance, unlike the notion of Lebesgue point. Let us think about these ideas in the setting of general metric spaces. The concept of Lipschitz mappings makes sense on any metric space. This method (12.2)

of blowing up a function at a point does not make sense on an arbitrary metric space, because there is no way to compare one ball with another. For many examples of metric spaces we can do this, for the examples described in Section 2 for instance. So what happens if we look for similar rigidity properties on other metric spaces?

Let us start with a Euclidean snowflake  $(\mathbb{R}^n, |x - y|^\alpha)$ ,  $0 < \alpha < 1$ . A Lipschitz function on this space is the same as a function on  $\mathbb{R}^n$  which is Hölder continuous of order  $\alpha$  with respect to the standard metric. For a Hölder continuous function of order  $\alpha$  the natural way to blow up at a point  $x$  is to take

$$g_{x,r}(h) = \frac{f(x + r h) - f(x)}{r^\alpha}. \quad (\text{B.12.3})$$

This family of functions on  $B(0, 1)$  is bounded if and only if the original function  $f$  is Hölder continuous of order  $\alpha$ . However there is no good limiting behavior for typical functions when  $0 < \alpha < 1$ . One can understand this in terms of Theorem 6.3 and Lemma 7.16. These results say that we can practically choose the behavior of Hölder continuous functions at different scales and locations independently of each other, which is incompatible with the existence of a limit.

This idea can be made very precise using Littlewood-Paley theory and wavelets. We shall not go into this here, but let us look at the classical example of lacunary trigonometric series. We work on the real line now, and we take  $f : \mathbb{R} \rightarrow \mathbb{R}$  to be of the form

$$f(y) = \sum_{j=1}^{\infty} a_j 2^{-j\alpha} \exp(2^j i y). \quad (\text{B.12.4})$$

Here  $\alpha > 0$ . If the  $a_j$ 's are bounded, then this series converges uniformly to a continuous function on  $\mathbb{R}$ . If  $\alpha < 1$  and the  $a_j$ 's are bounded, then  $f$  is Hölder continuous of order  $\alpha$ , as one can check using Theorem 6.3. In fact the boundedness of the  $a_j$ 's is necessary for  $f$  to be Hölder continuous of order  $\alpha$ .

What happens if we want  $f$  to be Lipschitz? This corresponds to  $\alpha = 1$ , but Theorem 6.3 does not apply to that case. In fact it cannot:

$$\text{If } f \text{ is Lipschitz, then } \sum_j |a_j|^2 < \infty. \quad (\text{B.12.5})$$

In particular we have to have  $a_j \rightarrow 0$  as  $j \rightarrow \infty$  in order for  $f$  to be Lipschitz, but square-summability is much stronger than that. It is easy to see why (12.5) has to be true. In order for  $f$  to be Lipschitz we have to have that  $f'(y)$ , taken in the sense of distributions, should be bounded.

Setting  $\alpha = 1$  in (12.4) we have that  $f'(y)$  is represented by the Fourier series

$$f'(y) = \sum_{j=1}^{\infty} i a_j \exp(2^j i y). \quad (\text{B.12.6})$$

In order for this to be bounded it should lie in  $L^2$  locally, and this periodic function lies in  $L^2$  if and only if  $\sum_j |a_j|^2 < \infty$ , by standard results about Fourier series.

It is not true that  $\sum_j |a_j|^2 < \infty$  implies that  $f$  is Lipschitz when  $\alpha = 1$ , but this is close to being true, in the sense that  $\sum_j |a_j|^2 < \infty$  implies that  $f'(y)$  exists almost everywhere and defines a function in  $L_{loc}^p$  for all  $p < \infty$ , and in fact that  $f' \in BMO(\mathbb{R})$ .

A nice fact: if  $f$  is as in (12.4) with  $\alpha = 1$ , and if  $f$  is differentiable at a single point, then  $a_j \rightarrow 0$  as  $j \rightarrow \infty$ . See the first corollary on p.106 of [Katzn].

The conclusion of this story is that nothing like differentiability almost everywhere holds for Hölder continuous functions of order  $< 1$ , and hence there is nothing like differentiability almost everywhere for Lipschitz functions on the Euclidean snowflakes  $(\mathbb{R}^n, |x - y|^\alpha)$ ,  $0 < \alpha < 1$ . Although Euclidean structure is pleasant for discussing lacunary Fourier series, approximately the same behavior can be found in Theorem 6.3 and Lemma 7.16. We should therefore not expect any rigidity like Theorem 12.1 on any metric space which can be realized as a snowflake.

What about other metric spaces? Is this kind of rigidity peculiar to spaces whose geometry is somehow approximately Euclidean? The lovely answer is no. There is a version of Theorem 12.1 for the Heisenberg groups. One has to be a little careful in defining the concept of differentiability almost everywhere for functions on the Heisenberg group, but it is basically the same as for Euclidean space. One uses translations and dilations to take snapshots of a given function, all snapshots living on the unit ball, and then one asks that the limit exist as  $r \rightarrow 0$ . The concept of linear mapping has to be modified. One looks for group homomorphisms instead. For real-valued mappings one looks for homomorphisms into the real numbers, but Pansu [Pan]<sub>CC</sub> established differentiability almost everywhere for Lipschitz mappings between Heisenberg groups too.

What about other examples? I do not know of any spaces where there is something like differentiability almost everywhere but where the geometry is not practically Euclidean or a relative of the Heisenberg group (or other Carnot groups, as in [Pan]<sub>CC</sub>). For a space like the Sierpinski carpet described in Section 2 one can hope for better behavior than Cantor sets and snowflakes (but not such good behavior as for Euclidean spaces

and Heisenberg groups), but I do not know a nice theorem. (See also the “GWALA” in [Dav–Sem]<sub>UR</sub>, and the discussion in [Sem]<sub>Map</sub>.)

### B.13. Pause for reflection.

The preceding discussion of differentiability almost everywhere provides us with a nice opportunity to view everything in Part II with deep suspicion. We see now that there are remarkable rigidity results to be found. There is nothing like that in Part II, and indeed nothing like Theorem 12.1 works at that level of generality.

In the next sections we shall consider other aspects of analysis and geometry more sensitive than those in Part II. Most of it will be about spaces with at least a little Euclidean structure. Measure theory will be crucial, as it is in Theorem 12.1. Good behavior typically does not occur in a uniform way for all points, only at most points. The idea of *BMO*, with uniform good behavior for 90% percent of the points, uniformly at all scales and locations, will play a large role.

Heisenberg geometry deserves more attention in this way, e.g., for the structure of mappings, recognizing when a space has approximately Heisenberg behavior, etc. Analysis on the Heisenberg group and its similarities to Euclidean analysis has been much studied (see [Fol–Ste]<sub>E<sup>st</sup></sub>, [Fol–Ste]<sub>HS</sub>, [Jer], [Stein]<sub>HA</sub>), but less attention has been paid to geometry (but see [Gro]<sub>CC</sub>).

There ought to be more to say about geometry and analysis on certain fractal sets than is available currently. Sierpinski carpets ought to behave better than snowflakes and Cantor sets if not as well as Euclidean spaces and Heisenberg groups. They have lots of rectifiable curves, for instance, although not so many as Euclidean space and the Heisenberg group. Sierpinski gaskets and fractal trees have fewer still but also enough to connect any pair of points. “Guy’s birdhouse” [David]<sub>MG</sub> is another example to consider. See [Barlow] and [Bar–Bass] for an interesting perspective on analysis on fractal sets.

Although Cantor sets have the least amount of structure in the examples that we have discussed, they too enjoy some interesting rigidity properties, as we shall see in Section 22.

### B.14. Almost flat curves.

Suppose that we have a curve in the plane whose length is only slightly larger than the distance between its endpoints. What can we say about this curve?

It is not hard to see that the curve must remain close to the line segment

between the endpoints. We can hope that its tangents must also be close to parallel to this line segment. This need not be true at all points, but it does have to be true at most points. One can always have a short arc in the curve that winds around as it pleases.

Let us be more precise and make computations. For reasons of simplicity and a larger agenda let us restrict ourselves to curves in the plane, and let us think of the plane as being  $\mathbb{C}$  instead of  $\mathbb{R}^2$ , for notation in particular. Let  $z : [a, b] \rightarrow \mathbb{C}$  be an arclength parameterization of our curve. This means that  $z(t)$  is 1-Lipschitz,  $|z'(t)| = 1$  almost everywhere, and the length of the curve is  $b - a$ . We have that

$$z(b) - z(a) = \int_a^b z'(t) dt, \quad (\text{B.14.1})$$

so that  $|z(b) - z(a)| \leq b - a$  automatically, and we are interested in the case where

$$b - a \leq (1 + \epsilon) |z(b) - z(a)| \quad (\text{B.14.2})$$

for a small  $\epsilon > 0$ .

Set  $\zeta = \frac{z(b) - z(a)}{b - a}$ , so that (14.2) is equivalent to

$$(1 + \epsilon)^{-1} \leq |\zeta| \leq 1. \quad (\text{B.14.3})$$

We would like to say that most of the tangents to our curve are almost parallel to  $\zeta$ , which is practically the same as saying that  $z'(t)$  is close to  $\zeta$  for most  $t$ . Indeed this is true, and we can compute in the same manner as [Coif–Mey]<sub>IC</sub>:

$$\int_a^b |z'(t) - \zeta|^2 dt = \int_a^b \{|z'(t)|^2 - z'(t) \bar{\zeta} - \bar{z}'(t) \zeta + |\zeta|^2\} dt. \quad (\text{B.14.4})$$

We can use (14.2) and the fact that  $|z'(t)| = 1$  almost everywhere to convert this into

$$\frac{1}{b - a} \int_a^b |z'(t) - \zeta|^2 dt = 1 - |\zeta|^2 - |\zeta|^2 + |\zeta|^2 = 1 - |\zeta|^2. \quad (\text{B.14.5})$$

Thus our flatness condition (14.2), (14.3) is equivalent to a bound on the  $L^2$  mean oscillation of  $z'(t)$  over  $[a, b]$ .

When thinking about (14.5) keep in mind that  $|z'(t)| = 1$  almost everywhere. The left side of (14.5) is small if and only if  $z'(t) - \zeta$  is small except for a set of  $t$ 's of small measure. Nothing too bad can happen on sets of small measure because  $|z'(t)|$  and  $|\zeta|$  are both bounded by 1.

In conclusion the flatness condition (14.2) holds with a small  $\epsilon$  if and only if  $z'(t)$  is almost constant on almost all of the interval  $[a, b]$ . We cannot get rid of the qualification “almost all of the interval”, because  $z'(t)$  could be practically anything on a small set without affecting (14.2) in a serious way.

Suppose now that we consider curves that are flat at all scales. So that the length of any subarc of the curve is only slightly larger than the distance between its endpoints. Can we say more then?

To be more precise, let us restrict ourselves to unbounded Jordan curves in the plane, and work again with parameterizations by arclength. Let  $z : \mathbb{R} \rightarrow \mathbb{C}$  be an arclength parameterization of our curve, so that  $z(t)$  is 1-Lipschitz and  $|z'(t)| = 1$  almost everywhere. We call this curve  $\epsilon$ -flat if

$$|s - t| \leq (1 + \epsilon) |z(s) - z(t)| \quad \text{for all } s, t \in \mathbb{R}, \quad (\text{B.14.6})$$

where  $\epsilon$  is some small positive number. This is equivalent to requiring that  $z : \mathbb{R} \rightarrow \mathbb{C}$  be a  $(1 + \epsilon)$ -bi-Lipschitz embedding.

With this stronger assumption of flatness at all scales and locations, can we conclude that  $z'(t)$  is a small perturbation of a constant everywhere? The answer is no, because there are very flat logarithmic spirals which satisfy this condition. Instead of checking this directly let us make a more general analysis. The flatness condition (14.6) is equivalent to the requirement that

$$\sup_{a, b \in \mathbb{R}} \frac{1}{b - a} \int_a^b |z'(t) - \zeta(a, b)|^2 dt \leq 1 - (1 + \epsilon)^{-2}, \quad (\text{B.14.7})$$

where  $\zeta(a, b) = \frac{z(b) - z(a)}{b - a}$  is the average of  $z'(t)$  over  $[a, b]$ . The left side of (14.7) is equivalent in size to the square of the *BMO* norm of  $z'(t)$  on  $\mathbb{R}$ . That is, the *BMO* norm was defined in (11.1), and it is easy to check that the left side of (14.7) is at least as big as the square of the *BMO* norm, because of the Cauchy-Schwarz inequality (i.e., the  $L^2$  norm is at least as big as the  $L^1$  norm). Conversely, the left side of (14.7) is bounded by a constant times the square of the *BMO* norm, because of the John-Nirenberg theorem mentioned in Section 11.

In short our curve is  $\epsilon$ -flat with a small  $\epsilon$  if and only if  $z'(t)$  has small *BMO* norm.

The requirement that  $z'(t)$  have small *BMO* norm turns out to be equivalent to the requirement that  $z'(t)$  can be written in the form  $z'(t) = \exp(ib(t))$ , where  $b(t)$  is a real-valued function on  $\mathbb{R}$  with small *BMO* norm. The sufficiency of this representation is not hard to see: bound on the

mean oscillation of  $b$  implies a similar bound for  $\exp(ib(t))$ , simply because  $\exp(ix)$  is a 1-Lipschitz function on  $\mathbb{R}$ . The converse is more subtle. In particular one has to be careful in taking the logarithm of  $z'(t)$ , because it can spin around and it will not be continuous in general. See [Coif–Mey]<sub>IC</sub> for details.

The bottom line here is quite simple. Given a real-valued function  $b(t)$  on  $\mathbb{R}$  with small  $BMO$  norm, we set

$$z(t) = z(0) + \int_0^t \exp(ib(s)) ds \quad (\text{B.14.8})$$

for some choice of  $z(0)$  (it doesn't matter which), and we get an  $\epsilon$ -flat curve where  $\epsilon$  is controlled in terms of the  $BMO$  norm of  $b$ . Conversely all  $\epsilon$ -flat curves arise this way, with a function  $b(t)$  whose  $BMO$  norm is controlled in terms of  $\epsilon$ . A basic example is given by  $b(t) = \delta \log|t|$ , where  $\delta$  is small, which corresponds to a flat logarithmic spiral.

Let us proceed now from small distortion to bounded distortion. We say that a curve is a chord-arc curve if the length of the arcs is always bounded by a constant multiple of the lengths of the chords, where now the constant can be large. More precisely, suppose that we are given a curve in the plane which is described by an arclength parameterization  $z : \mathbb{R} \rightarrow \mathbb{C}$ , and let us ask that there exist a constant  $k > 1$  such that

$$|s - t| \leq k |z(s) - z(t)| \quad \text{for all } s, t \in \mathbb{R}. \quad (\text{B.14.9})$$

This means that  $z : \mathbb{R} \rightarrow \mathbb{C}$  is  $k$ -bi-Lipschitz. What can we say now?

We can try again to represent  $z'(t)$  as  $\exp(ib(t))$  in a good way. We can always do this brutally, just taking the principal branch of the logarithm, but this does not respect the geometry very well. For instance we want a representation in which  $b(t)$  would be continuous if  $z'(t)$  were continuous.

Such a careful choice of logarithm is possible and was carried out in [David]<sub>CL</sub>. Unfortunately there is not a simple characterization of the functions  $b(t)$  that arise this way. They lie in  $BMO$ , but this necessary condition is not sufficient. Let us call  $\Omega$  the set of real-valued  $BMO$  functions that arise in this manner, through David's logarithm. What can we say about  $\Omega$ ? Not a whole lot, but the basic true fact is that  $\Omega$  is an open subset of  $BMO$ . (The openness comes from the exponential integrability estimates for  $BMO$  functions provided by the John-Nirenberg theorem.)

This is a gorgeous little fact. It turns out to be incredibly natural. It gives a topology to the space of chord-arc curves, and the work of Coifman and Meyer shows that certain operators associated to these curves

depend continuously on the curves with respect to this topology, even real-analytically. This works in a very sharp way, the  $BMO$  topology for curves corresponding exactly to the norm topology for operators. They also have a theorem on the real-analyticity of the correspondence between chord-arc curves and their Riemann mappings. See [Coif–Mey]<sub>VR</sub>, [Coif–Mey]<sub>IC</sub>, [Coif–Mey]<sub>LC</sub>, [Coif–Dav–Mey], and the survey paper [Sem]<sub>CIQM</sub> for more information. See [Sem]<sub>CTCI</sub>, [Sem]<sub>QM</sub> for an alternate approach.

It is not known whether the space  $\Omega$  of chord-arc curves is connected in the  $BMO$  topology.

### B.15. Mappings that almost preserve distances.

Suppose that  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  is  $(1 + \epsilon)$ -bi-Lipschitz for some small  $\epsilon > 0$ , so that  $f$  distorts distances by at most a factor of  $1 + \epsilon$ . (Remember (2.7).) What can we say about  $f$ ?

If  $\epsilon = 0$  then  $f$  must be a rigid mapping, a combination of a translation and an orthogonal mapping.

When  $\epsilon$  is small, in what sense does  $f$  have to be close to a rigid mapping? To what extent must its differential be almost constant?

Let us consider some examples.

Suppose first that  $f$  is of the form  $f(x) = x + \phi(x)$ , where  $\phi : \mathbb{R}^n \rightarrow \mathbb{R}^n$  has small Lipschitz norm. Then  $f$  is bi-Lipschitz with constant close to 1. These are the simplest mappings of this type.

Now suppose that  $f$  is of the form  $f(x) = R_{\log|x|}x$  when  $x \neq 0$ ,  $f(0) = 0$ , where  $R_t$ ,  $-\infty < t < \infty$ , is a one-parameter family of rotations on  $\mathbb{R}^n$  which is Lipschitz in  $t$  with small constant (with respect to any fixed norm on matrices). Then  $f$  is bi-Lipschitz with a small constant that depends only on the Lipschitz constant of  $R_t$  as a function of  $t$ . This is not so hard to check. This shows that a  $(1 + \epsilon)$ -bi-Lipschitz mapping on  $\mathbb{R}^n$  can make an infinite amount of spiralling no matter how small  $\epsilon$  is.

Thus a  $(1 + \epsilon)$ -bi-Lipschitz mapping  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  need not have its differential be almost constant in a uniform way. Slightly sad but true, like the story of the preceding section. So is the differential almost constant in an average sense? This is true, a theorem of John [John]. He did not say it this way, but what he proved was that the differential has small  $BMO$  norm. In fact  $BMO$  and the John-Nirenberg theorem (discussed in Section 11) began for this problem.

There is a very nice connection here with linear analysis. If one linearizes this problem – think of writing  $f$  as  $f(x) = x + \delta g(x)$ , looking at what happens when  $\delta$  is small, and neglecting terms of order  $\delta^2$  or higher – then one faces the following question. Suppose that  $g : \mathbb{R}^n \rightarrow \mathbb{R}^n$  has

the property that the symmetric part of its differential is bounded. (The differential is a matrix-valued function, so that “symmetric part” makes sense.) What can we say about  $g$ ? About its differential as a whole? It turns out that the antisymmetric part of the differential can be obtained from the symmetric part through singular integral operators, in a manner analogous to the formula (8.4) for obtaining mixed second partial derivatives of a function from the Laplacian. As usual these singular integral operators do not map bounded functions to bounded functions, but map bounded functions into  $BMO$ .

If it were true that the differential of a  $(1 + \epsilon)$ -bi-Lipschitz mapping  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  had to be a small perturbation of a constant in the  $L^\infty$  norm, then we would be able to conclude that  $f$  is a small perturbation of a rigid transformation in the Lipschitz norm. Now that we know that the differential of  $f$  is a small perturbation of a constant at most points inside a given ball, what can we say about  $f$  itself? In fact it is true that on a given ball  $B$  there is a rigid mapping  $\phi$  such that  $f - \phi$  has small Lipschitz norm when  $f - \phi$  is restricted to a subset of  $B$  which contains 90% of the points (in terms of Lebesgue measure). This can be derived from John’s theorem and standard facts in analysis (based on maximal functions, as discussed in Sections 35 and 36 below).

Let us now sketch a proof of the fact that if  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  is  $(1 + \epsilon)$ -bi-Lipschitz for some small  $\epsilon > 0$ , then the differential has small  $BMO$  norm. We shall not worry about getting explicit estimates (but see [John]), just the fact that the  $BMO$  norm is small. Of course the differential is bounded, so we have to show that the  $BMO$  norm is *small* to get any information.

The first observation to make is that if  $B$  is a ball in  $\mathbb{R}^n$  of radius  $r$ , then we can find a rigid mapping  $\phi : \mathbb{R}^n \rightarrow \mathbb{R}^n$  such that

$$r^{-1} \sup_{y \in B} |f(y) - \phi(y)| \tag{B.15.1}$$

is small, i.e., it is bounded by a function of  $\epsilon$  which goes to 0 as  $\epsilon \rightarrow 0$  and which does not depend on  $f$  or  $B$ . One can give direct proofs of this, but a very simple way to do it is to use compactness. If this is not true, then one can find a sequence of  $(1 + \epsilon_j)$ -bi-Lipschitz mappings  $f_j : \mathbb{R}^n \rightarrow \mathbb{R}^n$  with  $\epsilon_j \rightarrow 0$  and a sequence of balls  $B_j$  such that the  $f_j$ ’s are not well approximated by rigid mappings on the  $B_j$ ’s, meaning that the quantities analogous to (15.1) are bounded away from 0. One can normalize with translations and dilations to reduce to the case where all the  $B_j$ ’s are the unit ball and  $f_j(0) = 0$  for all  $j$ . One can then use the Arzela-Ascoli theorem to pass to a subsequence to conclude that the  $f_j$ ’s converge uniformly on compact sets to a mapping  $g : \mathbb{R}^n \rightarrow \mathbb{R}^n$ . This limiting mapping must be

1-bi-Lipschitz and hence rigid. This contradicts the original assumption that the  $f_j$ 's are uniformly far from rigid mappings on the balls  $B_j$ , and so we get our approximation result.

This compactness argument is somewhat revolting for being nonconstructive and not providing explicit bounds, but it is quick and easy.

To show that the differential has small  $BMO$  norm we have to show that it is almost constant on most of any ball. This is a stronger statement than (15.1), because it is a condition on the derivative of  $f$ . Let a ball  $B$  of radius  $r$  be given. Let us assume that

$$r^{-1} \sup_{y \in 2B} |f(y) - y| \quad (\text{B.15.2})$$

is small. We can do this because of (15.1), and because we may normalize  $f$  by composing it with a rigid mapping without changing the problem. Note that we have replaced  $B$  by  $2B$  here, to give ourselves some extra room as a precaution.

Fix a point  $x \in B$  and another point  $z$  with  $|x - z| = r$ . Consider the line segment  $S$  that connects  $x$  to  $z$ . The restriction of  $f$  to  $S$  defines a rectifiable curve of length  $\leq (1 + \epsilon)r$ , since  $f$  is  $(1 + \epsilon)$ -bi-Lipschitz. On the other hand the image of  $S$  under  $f$  remains very close to  $S$ , and in particular

$$r^{-1} \max(|f(x) - x|, |f(z) - z|) \quad (\text{B.15.3})$$

must be small. Thus the distance between the endpoints of this curve is close to  $r$ . Let  $v$  denote the unit vector  $\frac{x-z}{|x-z|}$ . If  $D_v f(p)$  denotes the directional derivative of  $f$  in the direction  $v$  at the point  $p$ , then it is not hard to show that

$$r^{-1} \int_S |D_v f(p) - v|^2 dp \quad (\text{B.15.4})$$

must be small. For instance one can make a calculation like the one in (14.4), (14.5), with the minor additional complication that the restriction of  $f$  to  $S$  does not provide an arclength parameterization of the image (but almost does, since  $f$  is  $(1 + \epsilon)$ -bi-Lipschitz). One can also make geometrical arguments to understand this. At any rate it is true.

Since this is true for all initial choices of  $x$  and  $z$  one can average over the various segments to show that

$$\frac{1}{|B|} \int_B |df(y) - I|^2 dy \quad (\text{B.15.5})$$

is small, where  $I$  denotes the identity matrix. This is exactly what we wanted, to show that the mean oscillation of the differential of  $f$  was small.

Actually, this is not quite the definition of mean oscillation that we used in (9.1), but it works just as well. We are using here an  $L^2$  integral instead of an  $L^1$  integral, which is all the better (by Cauchy-Schwarz). We have not said that  $I$  is the mean value of  $df$  on  $B$ , but that doesn't matter; as soon as one has a bound for (15.5) one gets a similar bound for the difference between  $I$  and the mean value of  $df$  on  $B$ .

This completes our sketch of the proof that  $df$  has small  $BMO$  norm.

### B.16. Almost flat hypersurfaces.

Let  $M$  be a hypersurface in  $\mathbb{R}^{d+1}$ . That is,  $M$  should be a  $d$ -dimensional embedded smooth submanifold, and we assume also that it is nice at infinity, asymptotic to a hyperplane for instance. This smoothness should be treated as an *a priori* assumption; we require it for technical convenience, but we want to have estimates which do not depend on this smoothness in a quantitative manner.

Let  $\epsilon > 0$  be given. We shall say that  $M$  is  $\epsilon$ -flat if the following two conditions are satisfied. First we ask that for each pair of points  $x, y \in M$  we have that

$$\text{there is a curve } \gamma \text{ in } M \text{ from } x \text{ to } y \text{ whose length is } \leq (1 + \epsilon) |x - y|. \quad (\text{B.16.1})$$

This means that the external Euclidean distance and the internal geodesic distance should be almost the same. The second condition is that for each  $x \in M$  and  $r > 0$  we have that

$$(1 - \epsilon) \nu_d r^d \leq |B(x, r) \cap M| \leq (1 + \epsilon) \nu_d r^d \quad (\text{B.16.2})$$

where  $|E|$  denotes the  $d$ -dimensional surface measure of  $E \subseteq M$  and  $\nu_d$  denotes the volume of the unit ball in  $\mathbb{R}^d$ . This means that the volume of a ball in  $M$  is practically the same as the volume of a ball of the same radius in flat space. The balls here are defined using the ambient Euclidean metric, but that does not really matter, because of (16.1).

In short  $M$  is  $\epsilon$ -flat if measurements of length and volume are the same to within factors of  $\epsilon$  of the corresponding measurements for flat space. Note that this concept reduces to the one in (14.6) when  $d = 1$ . Notice also that this condition is scale-invariant; if we take an  $\epsilon$ -flat hypersurface and act on it by a translation, dilation, or a rotation, then we get another  $\epsilon$ -flat hypersurface, with the same choice of  $\epsilon$ .

So are  $\epsilon$ -flat hypersurfaces really flat in some reasonable sense? One can show that they are always well-approximated by hyperplanes locally

(in the Hausdorff metric), but this is not at all the whole story. The basic question is the following.

**B.16.3. Question:** *If  $M$  is an  $\epsilon$ -flat hypersurface in  $\mathbb{R}^{d+1}$ , and if  $\epsilon$  is small enough, does there exist a  $(1 + \delta)$ -bi-Lipschitz mapping  $f$  from  $\mathbb{R}^d$  onto  $M$ , where  $\delta$  depends only on  $\epsilon$  and the dimension, and  $\delta \rightarrow 0$  as  $\epsilon \rightarrow 0$ ?*

A  $(1 + \delta)$ -bi-Lipschitz mapping is just one that distorts distances by at most a factor of  $1 + \delta$ , as in (2.7). If  $f : \mathbb{R}^d \rightarrow \mathbb{R}^{d+1}$  is  $(1 + \delta)$ -bi-Lipschitz, then  $M = f(\mathbb{R}^d)$  satisfies (16.1) and (16.2) with an  $\epsilon$  which is controlled in terms of  $\delta$  and which goes to zero when  $\delta \rightarrow 0$ . Question 16.3 asks for the converse to this easy observation.

Notice that  $\epsilon$ -flat hypersurfaces do not have to be graphs — they can have spirals. We saw this for curves in Section 14, and in higher dimensions we saw in Section 15 that  $(1 + \delta)$ -bi-Lipschitz mappings on Euclidean spaces can spiral around (slowly!) no matter how small  $\delta$  is.

The answer to Question 16.3 is yes when  $d = 1$ , because the arc length parameterization provides such a mapping. In higher dimensions this does not work so easily, because there is nothing like the arclength parameterization. Indeed Question 16.3 remains unsolved for all  $d > 1$ . It is not even known whether an  $\epsilon$ -flat hypersurface always admits a  $C$ -bi-Lipschitz parameterization when  $\epsilon$  is small enough and  $C$  depends only on the dimension.

On the other hand, one can prove directly that  $\epsilon$ -flat surfaces enjoy many of the properties that would hold if the answer to Question 16.3 is yes. For instance  $\epsilon$ -flat hypersurfaces are homeomorphic to  $\mathbb{R}^d$  when  $\epsilon$  is small enough. One can build parameterizations with  $L^p$  bounds on their differentials and on the differentials of their inverse mappings, with  $p \rightarrow \infty$  as  $\epsilon \rightarrow 0$ . (See [Sem]SC2.) The construction proceeds through an infinite series of approximations, and in order to get bi-Lipschitz estimates one would have to show that the distortion of distance does not get too large anywhere. This seems to be very difficult. If one is willing to settle for  $L^p$  bounds for the differential with a  $p < \infty$ , then it suffices to show that the distortions of distances accumulate only on a small set, and this is much easier to accomplish.

The construction of these parameterizations with  $L^p$  bounds proceeds through geometric versions of Calderón-Zygmund approximations. The latter are discussed in a more classical form for analysis in Section 39 below.

There are also nice characterizations of  $\epsilon$ -flat hypersurfaces in terms of analysis, in terms of the almost-orthogonality of a certain decomposition of  $L^2(M)$ . See [Sem]SC1. These results would be easier to prove if the answer to Question 16.4 were yes, but one can argue directly without knowing that.

I am inclined to believe that the answer to Question 16.3 is no.

There are versions of Question 16.3 for quasisymmetric mappings. One should be a little careful in formulating the appropriate “almost flat” version of the quasisymmetry condition, but this is not a serious problem. In dimension 2 one can find quasisymmetric parameterizations (see [Sem]<sub>SC2</sub>, [Hein–Kosk]<sub>DQC</sub>), but this is not known in higher dimensions. The main point of the argument in [Sem]<sub>SC2</sub> was to use the uniformization theorem to find a conformal parameterization, and then to use geometric methods to obtain bounds for this conformal mapping. The results of [Hein–Kosk]<sub>DQC</sub> permit one to obtain estimates in any dimension as soon as there is a conformal or even a quasiconformal parameterization, but in dimensions larger than 2 they are not so easy to come by. Again I am inclined to believe that they do not exist in general.

To place this question in a larger context let us consider a variant of it formulated in terms of curvature. Let  $M$  be a hypersurface in  $\mathbb{R}^{d+1}$ , and let  $k(x)$  denote the maximum of the (absolute values) of the principal curvatures of  $M$  at  $x$ . This measures the size of the derivative of the unit normal vector to  $M$  at  $x$ . Consider the condition

$$\int_M k(x)^d dx \leq \gamma, \quad (\text{B.16.4})$$

where  $dx$  denotes surface measure on  $M$ , and  $\gamma$  is a small number. This says that the curvature is small on average, so that the hypersurface ought to be pretty flat. In fact this condition implies  $\epsilon$ -flatness when  $\gamma$  is small enough, with an  $\epsilon$  which is controlled by  $\gamma$  and which tends to zero with  $\gamma$ . (See [Sem]<sub>BMO</sub>.) This condition on curvature is stronger than  $\epsilon$ -flatness, because it involves more derivatives, but it shares with  $\epsilon$ -flatness the property of being scale-invariant. When  $d = 1$  the integral in (16.4) controls the maximal oscillation of the unit normal to  $M$ , and  $M$  can be represented as the graph over a line of a Lipschitz function which has small Lipschitz norm. When  $d > 1$  (16.4) permits  $M$  to have infinite spirals, but they have to be slower than the ones permitted by  $\epsilon$ -flatness.

When  $d = 2$  it turns out that (16.4) is sufficient to imply the existence of a  $(1 + \delta)$ -bi-Lipschitz parameterization with  $\delta$  controlled by  $\gamma$ , and with  $\delta \rightarrow 0$  as  $\gamma \rightarrow 0$ . This was proved in [Toro]<sub>SFF</sub>. When  $d > 2$  this is not known, although there is a related criterion for the existence of such parameterizations in terms of flatness conditions in [Toro]<sub>BP</sub>.

The curvature condition (16.4) is related to  $\epsilon$ -flatness through a geometric version of the Sobolev embedding theorem. We have seen in (11.4) how the  $BMO$  norm of a function on  $\mathbb{R}^d$  is controlled by the  $L^d$  norm of its gradient. The situation here is very similar. Let  $M$  by a hypersurface

in  $\mathbb{R}^{d+1}$ , and let  $n(x)$  denote a (smooth) choice of unit normal vector to  $M$ . The curvature condition (16.4) says that the gradient of  $n(x)$  as a vector-valued function on  $M$  has small  $L^d$ -norm on  $M$ . If we have something like (11.4) for functions on  $M$ , then we can conclude that  $n(x)$  has small  $BMO$  norm on  $M$ , i.e., that  $\|n\|_*$  is small, where  $\|n\|_*$  is defined as in (11.1), using (9.1) (with  $\mu$  taken to be the volume measure on  $M$ ). It is not true that an estimate like (11.4) holds for all hypersurfaces in  $\mathbb{R}^{d+1}$ , and indeed this becomes wrong when the hypersurface has a big balloon with a small neck. It turns out that this cannot happen when (16.4) is true (with  $\gamma$  small), and there are suitable Poincaré inequalities in this case. See [Simon], [Sem]<sub>BMO</sub>. Thus the curvature condition implies that  $\|n\|_*$  is small. It also happens that  $\epsilon$ -flatness with small  $\epsilon$  is equivalent to  $\|n\|_*$  being small. (See [Sem]<sub>SC1</sub>, [Sem]<sub>BMO</sub>.)

Here again we see how  $BMO$  arises naturally in a geometric problem. There is also a natural measure-theoretic aspect of this story. Although we do not know the answer to Question 16.3, we do know that given any ball  $B$  centered on  $M$  we can parameterize 90% of  $B \cap M$  by a subset of  $\mathbb{R}^d$  using a  $(1 + \delta)$ -bi-Lipschitz mapping. Actually we can do much better than that, we can realize 90% of  $B \cap M$  as a subset of a graph over a hyperplane of a Lipschitz function with small norm. (See [Sem]<sub>SC1</sub>.)

These geometric statements arise in the following manner. It turns out that for each ball  $B$  centered on  $M$  there is a hyperplane that approximates  $M$  very well in  $B$ . One has to understand how this hyperplane turns around as we move from ball to ball, or as we shrink a ball to a point. One can choose the hyperplane so that it is orthogonal to the average of  $n$  on  $B$ . This leads us to the analytical problem of understanding how the averages of a  $BMO$  function can oscillate as we move around. This question can be analyzed using “maximal functions”, as discussed in Sections 32 and 42 below.

### B.17. The $A_\infty$ condition for doubling measures.

What does it mean for two measures to be almost the same? What is a good way to formulate this idea? We can start with the condition that each be bounded by a constant multiple of the other, but that is too limited.

Recall that a measure  $\alpha$  on some measure space is said to be *absolutely continuous* with respect to a measure  $\beta$  if any set with measure zero with respect to  $\beta$  has measure zero with respect to  $\alpha$ . The Radon-Nikodym theorem states that if  $\alpha$  and  $\beta$  are finite measures, then  $\alpha$  is absolutely continuous with respect to  $\beta$  if and only if  $\alpha$  is of the form  $\alpha = f\beta$ , where  $f$  is an integrable function with respect to  $\beta$ .

If  $\alpha$  and  $\beta$  are finite measures, then  $\alpha$  is absolutely continuous with respect to  $\beta$  if and only if for every  $\epsilon > 0$  there is a  $\delta > 0$  so that

$$\beta(E) < \delta \quad \text{implies} \quad \alpha(E) < \epsilon \quad (\text{B.17.1})$$

for each measurable set  $E$ . The “if” part is trivial, and the “only if” part can be derived from the Radon-Nikodym theorem.

We shall need here a stronger notion of absolute continuity, a property that takes geometry into account and is scale invariant. Let  $\mu$  be a doubling measure on  $\mathbb{R}^n$ . We say that  $\mu$  is an  $A_\infty$  measure, if for each  $\epsilon > 0$ , there exists a  $\delta > 0$  so that given any ball  $B$  in  $\mathbb{R}^n$  and any measurable subset  $E$  of  $B$  we have that

$$\frac{|E|}{|B|} < \delta \quad \text{implies} \quad \frac{\mu(E)}{\mu(B)} < \epsilon, \quad (\text{B.17.2})$$

where  $|E|$  denotes the Lebesgue measure of  $E$ . This sentence is a mouthful, let us take it slowly. The condition (17.2) looks like (17.1), and it implies that  $\mu$  is absolutely continuous with respect to Lebesgue measure, but it is stronger than that because it requires that a single  $\delta$  works for all balls  $B$ .

Because the  $A_\infty$  condition implies absolute continuity we can write an  $A_\infty$  measure  $\mu$  as  $\mu = \omega(x) dx$  for some locally integrable function  $\omega(x)$  on  $\mathbb{R}^n$ . These functions are called  $A_\infty$  weights, and in the harmonic analysis literature the  $A_\infty$  condition is normally stated directly in terms of the density.

What are examples of  $A_\infty$  weights? Any positive function  $\omega(x)$  which is bounded and bounded away from 0 is an  $A_\infty$  weight. Some of the examples of doubling measures on  $\mathbb{R}^n$  mentioned in Section 3 are actually  $A_\infty$  measures. For instance  $\omega(x) = |x|^a$  is an  $A_\infty$  weight on  $\mathbb{R}^n$  for all  $a > -n$ , and  $\omega(x) = |x_1|^b$  is an  $A_\infty$  weight on  $\mathbb{R}^n$  when  $b > -1$ . If  $K$  denotes the usual middle-thirds Cantor set, then  $\text{dist}(x, K)^s$  is an  $A_\infty$  weight on  $\mathbb{R}$  for a range of  $s$ 's that one can compute and which is the same as the range for which it is locally integrable. (All  $s \geq 0$  are allowed, and some negative  $s$ 's too.)

The  $A_\infty$  condition has the nice property that it is equivalent in nontrivial ways to several other conditions. For instance, it is enough to ask that *there exist*  $\epsilon, \delta \in (0, 1)$  such that (17.2) holds. A priori this is much weaker than the definition above, in which we ask that for every  $\epsilon$  there is a  $\delta$ , but there is a way to iterate this weaker version of (17.2) to get the stronger version. The  $A_\infty$  condition is also equivalent to the apparently stronger requirement that there exist  $C, a > 0$  so that

$$\frac{\mu(E)}{\mu(B)} \leq C \left( \frac{|E|}{|B|} \right)^a \quad (\text{B.17.3})$$

for all balls  $B$  and all measurable subsets  $E$  of  $B$ . These equivalences are analogous to the results of John-Nirenberg and Strömberg about  $BMO$  mentioned in Section 11, and they are discussed again in Section 41.

In fact  $A_\infty$  weights enjoy a very close analogy with  $BMO$ ; they are a multiplicative cousin of  $BMO$ . The  $A_\infty$  condition is not disturbed if we multiply the weight by a positive constant, the choices of  $\epsilon$  and  $\delta$  (or  $C$  and  $a$  in (17.3)) are unaffected by this multiplication. This corresponds to the fact that the  $BMO$  norm of a function is not changed if one adds a constant to the function. If  $\omega(x)$  is an  $A_\infty$  weight and  $B$  is a ball, then there is a positive constant  $\lambda$  (the average of  $\omega$  over  $B$  will work) so that  $\omega(x)$  lies within a bounded factor of  $\lambda$  for 90% of the points  $x \in B$ , where the bounded factor does not depend on  $B$ . This corresponds to the theorem of Strömberg mentioned in Section 11.

There are concrete facts behind this similarity between  $A_\infty$  weights and  $BMO$ . If  $b$  is a (real-valued)  $BMO$  function on  $\mathbb{R}^n$  with sufficiently small  $BMO$  norm, then  $\omega = e^b$  is an  $A_\infty$  weight. This can be proved using the John-Nirenberg theorem. Conversely, if  $\omega$  is an  $A_\infty$  weight, then  $\log \omega$  lies in  $BMO$ . It is not true that if  $b$  is any  $BMO$  function, then  $e^b$  is an  $A_\infty$  weight, and indeed  $e^b$  may not even be locally integrable. One is faced with the subset

$$\{\log \omega : \omega \text{ is an } A_\infty \text{ weight}\} \quad (\text{B.17.4})$$

of  $BMO$ , which turns out to be convex and open. (Compare with Section 14.)

That (17.4) defines an *open* subset of  $BMO$  is especially nice and connected to other basic facts about  $A_\infty$  weights. A particularly important result is that a positive locally integrable function  $\omega(x)$  is an  $A_\infty$  weight if and only if it satisfies a reverse Hölder inequality, which means that there exists a constant  $C > 0$  and an exponent  $p > 1$  such that

$$\left( \frac{1}{|B|} \int_B \omega(x)^p dx \right)^{\frac{1}{p}} \leq C \frac{1}{|B|} \int_B \omega(x) dx \quad (\text{B.17.5})$$

for all balls  $B$ . This may look strange but it is very nice. It says first of all that  $\omega$  actually lies in  $L_{loc}^p$  for some  $p > 1$ , and not just in  $L_{loc}^1$ . The inequality (17.5) would not mean as much if  $C$  were allowed to depend on  $B$ , but by having uniform estimates for all balls (17.5) imposes much stronger constraints on the oscillation of  $\omega$ .

Note that (17.3) can be derived from (17.5) using Hölder's inequality. The openness of (17.4) in  $BMO$  can be proved using (17.5) and the John-Nirenberg theorem. See Section 41 for an explanation of how to get the reverse Hölder inequality (17.5).

One can think of the concept of an  $A_\infty$  weight as providing a way to perturb Lebesgue measure without making too much of a change. For instance, if we define  $BMO$  relative to an  $A_\infty$  weight instead of Lebesgue measure, then the resulting space is the same as  $BMO$  for Lebesgue measure. (There is a converse to this due to Peter Jones, and also results of Reimann for quasiconformal mappings.)  $A_\infty$  weights and their more refined cousins the  $A_p$  weights cooperate well with singular integral operators. They also show up on their own, in connection with Riemann mappings and harmonic measure, for instance.

The  $A_\infty$  condition has an important symmetry property. We defined the concept of an  $A_\infty$  measure relative to Lebesgue measure, but we could have replaced Lebesgue measure by any other doubling measure. Indeed the theory actually works on spaces of homogeneous type, so that it makes sense to say that one doubling measure enjoys the  $A_\infty$  property with respect to another. It turns out that the  $A_\infty$  property defines an equivalence relation. The transitivity follows easily from the characterization (17.2) with the quantifiers “for every  $\epsilon > 0$  there is a  $\delta > 0$ ”, while the symmetry follows from (17.2) with the quantifiers “there exist  $\epsilon, \delta \in (0, 1)$ ”. Note that the transitivity works in the same as way as for absolute continuity but the symmetry is fundamentally different.

Thus we have the concept of deforming a doubling measure by an  $A_\infty$  weight, and we expect that this deformation is pretty mild. This idea has a nice geometric version. We saw in (3.6) how to associate a quasimetric to a doubling measure. If we apply this construction to two doubling measures which are  $A_\infty$  equivalent, then on 90% of any given ball the two quasimetries will look approximately the same, except for a scale factor. That is, after making a rescaling (multiplying by a positive constant), the two quasimetries will each be less than a bounded multiple of the other on 90% of the ball. This can be proved using some information from “maximal functions”, as in Lemma 42.5.

The concept of “90% of the points in the ball” captures well the idea of the  $A_\infty$  condition. The statement that two doubling measures are  $A_\infty$  equivalent means roughly that they both have the same concept of “90% of the points in a ball” even though they may give very different measures to the same set. In this statement the concept of 90% should be taken somewhat figuratively as a way of saying nearly all. The number 90 is not special, just evocative. In passing from one measure to another which is  $A_\infty$  equivalent the percentages might have to change, but the point is that the concept of “nearly all” remains the same, in a way that is made precise by (17.2).

See [Garn], [Jour], and [Stein]<sub>HA</sub> for more information about  $A_\infty$  weights.

### B.18. Quasisymmetric mappings and doubling measures.

Suppose that  $f$  is a quasisymmetric mapping from  $\mathbb{R}^n$  onto itself, and let  $\mu$  be the measure on  $\mathbb{R}^n$  obtained by pulling back Lebesgue measure using  $f$ , i.e.,  $\mu(E) = |f(E)|$ . What can we say about  $\mu$ ? It is easy to see that  $\mu$  is a doubling measure. When  $n = 1$  we cannot say anything more than that. Given any doubling measure on the line we can integrate it to get a quasisymmetric homeomorphism on the line so that the given doubling measure is the pull-back of Lebesgue measure.

What happens in higher dimensions? It is not so easy to integrate a measure and get a mapping.

**B.18.1. Theorem (Gehring [Gehring]):** *If  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  is quasisymmetric and the measure  $\mu$  is defined by  $\mu(E) = |f(E)|$ , and if  $n > 1$ , then  $\mu$  is an  $A_\infty$  measure (as defined in the previous section). In particular it is absolutely continuous with respect to Lebesgue measure and its density lies in  $L_{loc}^p$  for some  $p > 1$ .*

This is a wonderful fact.

Why exactly is dimension 1 different from higher dimensions here? It comes down to the ancient length-area principle, that quasisymmetric mappings have to distort length and area in approximately the same way. This does not mean much in dimension 1, where length and “area” are the same. In order to get to the central point let us assume that  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  is quasisymmetric and also smooth. In this case we have that

$$\sup_{|v|=1} |df_x(v)| \leq K \inf_{|v|=1} |df_x(v)|, \quad (\text{B.18.2})$$

where  $df_x$  denotes the differential of  $f$  at  $x$  – the linear mapping provided by calculus which best approximates the behavior of  $f$  at  $x$  – and  $K$  is a constant that depends only on the function that governs the quasisymmetry of  $f$  (the function  $\eta$  in Definition 4.1). The supremum and infimum in (18.2) are taken over all unit vectors  $v \in \mathbb{R}^n$ , and (18.2) says that the maximal stretch of the differential is always bounded by the minimal stretch, even though these numbers may be very small or very large. A diffeomorphism  $f$  on  $\mathbb{R}^n$  which satisfies (18.2) is said to be  $K$ -quasiconformal, and it turns out that the concepts of quasiconformality and quasisymmetry are equivalent on Euclidean spaces, modulo technicalities pertaining to differentiability assumptions.

Now let  $Q$  be a cube in  $\mathbb{R}^n$ , and let us study the relationship between the distortion of length and area by  $f$  near  $Q$ . Let  $\omega(x)$  denote the Jacobian of  $f$  at  $x$  (the determinant of  $df_x$ ). The measure  $\mu$  associated to  $f$  as in the

statement of Theorem 18.1 is given by  $\mu = \omega(x) dx$ . We have that

$$\int_Q \omega(x) dx \leq C (\operatorname{diam} f(Q))^n, \quad (\text{B.18.3})$$

where  $C$  depends only on  $n$  and the function that governs the quasisymmetry of  $f$ . Indeed, the left hand side is just the volume of  $f(Q)$ , and this volume is bounded by the right side of (18.3).

On the other hand, let  $\sigma$  be a line segment that connects two of the opposite faces of  $Q$ . Let us check that

$$\int_\sigma \omega(z)^{\frac{1}{n}} dz \geq C^{-1} \operatorname{diam} f(Q) \quad (\text{B.18.4})$$

for a suitable constant  $C$ , where the  $dz$  in the integral denotes the arclength measure. Indeed, we have that  $|df_z| \leq K \omega(z)^{\frac{1}{n}}$ , because of (18.2). This implies that the integral on the left side of (18.4) is larger than a multiple of the length of  $f(\sigma)$ , and hence of  $\operatorname{diam} f(\sigma)$ . The quasisymmetry condition implies that  $\operatorname{diam} f(Q)$  is bounded by a multiple of  $\operatorname{diam} f(\sigma)$ , and (18.4) follows.

In this way we are able to conclude that

$$\left( \frac{1}{|Q|} \int_Q \omega(x) dx \right)^{\frac{1}{n}} \leq C \frac{1}{\operatorname{diam} Q} \int_\sigma \omega(z)^{\frac{1}{n}} dz \quad (\text{B.18.5})$$

whenever  $\sigma$  is a line segment which connects opposite faces of  $Q$ . By averaging over  $\sigma$  we can convert this to

$$\left( \frac{1}{|Q|} \int_Q \omega(x) dx \right)^{\frac{1}{n}} \leq C \frac{1}{|Q|} \int_Q \omega(x)^{\frac{1}{n}} dx. \quad (\text{B.18.6})$$

This is an interesting inequality. It contains no information whatsoever when  $n = 1$ . When  $n > 1$  it is a reverse Hölder inequality, similar to (17.5). That is, the average of  $\omega$  over a cube is controlled by the  $L^s$  average over the cube, where  $s = 1/n < 1$ . Gehring proved that once we have such a reverse Hölder inequality we can get a slightly better one, i.e., there exist constants  $M, p > 1$  depending on  $C$  and  $n$  from (18.6) such that

$$\left( \frac{1}{|Q|} \int_Q \omega(x)^p dx \right)^{\frac{1}{p}} \leq M \left( \frac{1}{|Q|} \int_Q \omega(x)^{\frac{1}{n}} dx \right)^n. \quad (\text{B.18.7})$$

(See also Section 41.) It is very important here that we know (18.6) for all cubes  $Q$ ; it is not true that (18.6) implies something like (18.7) for each fixed cube separately.

It is also important here that the constants in (18.7) depend finally only on the dimension  $n$  and the function that governs the quasisymmetry of  $f$ . The bottom line is that  $\omega$  satisfies a reverse Hölder inequality like (17.5), but with balls replaced by cubes, which does not matter. This permits us to conclude that  $\omega$  is an  $A_\infty$  weight, with bounds that depend only on  $n$  and the function that governs the quasisymmetry of  $f$ .

This does not quite prove Theorem 18.1, because of our a priori smoothness assumption on  $f$ , but it does cover the main points.

Gehring's theorem is quite remarkable because it provides very strong restrictions on the way in which quasisymmetric mappings on  $\mathbb{R}^n$  can distort distances when  $n > 1$ . It provides a much stronger restriction than is given directly by the definition, or indeed which is true in general, i.e., than what is true on the real line, or on Cantor sets. For instance, it implies that if  $B$  is a ball in  $\mathbb{R}^n$ ,  $n > 1$ , and  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  is quasisymmetric, then  $f$  is actually bi-Lipschitz on 90% of  $B$ . In fact, one can normalize  $f$  by a scale factor on  $B$  to get a uniform bound on the bi-Lipschitz constant. These assertions can be derived from Lemma 42.5 below.

Notice that the quasisymmetry condition is not disturbed by composing the mapping with a dilation. Any estimates that we can hope to get for the distortion of distances by quasisymmetric mappings has to respect that. This corresponds nicely to the fact that the  $A_\infty$  condition is not disturbed by multiplying the weight by a multiplicative constant.

One might wonder whether Theorem 18.1 has counterparts for other metric spaces. Other regular metric spaces (Definition 3.8), for instance, for which the formulation of the statement still makes sense (with the measure provided in Definition 3.8 playing the role of Lebesgue measure). It doesn't work for Cantor sets, but it does work for a lot of other spaces. A criterion in terms of the existence of Poincaré inequalities is given in [Hein–Kosk]<sub>QCC</sub>. Gehring's argument can be adapted to situations where there are plenty of curves around that are not too long, e.g., a metric space of the form  $N \times \mathbb{R}$  would work, where  $N$  is a (regular) metric space. A different variation on Gehring's theme is given in [Sem]<sub>Quasi</sub>. It is not clear yet what is really the right context for Gehring's theorem though.

Presumably one can say more for Sierpinski carpets than for Cantor sets, but less than for Euclidean spaces.

### B.19. Metric doubling measures.

Does every  $A_\infty$  measure on  $\mathbb{R}^n$  arise as in Gehring's theorem? When  $n = 1$  the answer is yes, because one can just integrate the measure. When  $n > 1$  this is less clear. We should give ourselves some room for maneuver;

let us ask whether it is true that for each  $A_\infty$  measure  $\mu$  on  $\mathbb{R}^n$  there is a quasisymmetric mapping  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  and a constant  $C > 0$  such that

$$C^{-1} \mu(E) \leq |f(E)| \leq C \mu(E) \quad (\text{B.19.1})$$

for all Borel sets  $E$ .

This is not true when  $n > 1$ . Take  $\mu = |x_1| dx$ , where  $x_1$  denotes the first coordinate function. One can check that this defines an  $A_\infty$  measure. However it cannot satisfy (19.1) for any quasisymmetric mapping  $f$ . If it did, one could show that the differential of  $f$  exists everywhere on the  $x_1 = 0$  hyperplane and vanishes, and conclude that  $f$  is constant there, a contradiction. More generally there is a problem when the density of  $\mu$  becomes too small on curves that are not too long.

In order to avoid this problem we make an additional assumption.

**B.19.2. Definition:** Let  $\mu$  be a doubling measure on  $\mathbb{R}^n$ , and define the associated quasimetric  $D(x, y)$  on  $\mathbb{R}^n$  as in (3.6), with  $\alpha = 1/n$ . We say that  $\mu$  is a metric doubling measure if there exists a constant  $C > 0$  and a metric  $\delta(x, y)$  on  $\mathbb{R}^n$  such that

$$C^{-1} \delta(x, y) \leq D(x, y) \leq C \delta(x, y) \quad (\text{B.19.3})$$

for all  $x, y \in \mathbb{R}^n$ .

In other words, the quasimetric  $D(x, y)$  associated to  $\mu$  is likely to not be a metric, but we ask that it be comparable to one in size. For instance,  $\mu = |x|^a dx$  has this property for all  $a > -1$ , but when  $n > 1$  the measure  $\mu = |x_1|^b dx$  has this property only when  $-1 < b \leq 0$ , even though we get a doubling measure for all  $b > -1$ . The problem is the same as the one above; if  $\mu$  gets too small near a curve that is not too long, and if  $\mu$  is a metric doubling measure, then we would get into trouble because  $\delta(x, y)$  would have to vanish for some pairs of points  $x, y$  with  $x \neq y$ . One can think of this as meaning that the  $D(x, y)$ -lengths of curves are not permitted to become too small when  $\mu$  is a metric doubling measure.

This concept was introduced in [Dav–Sem]<sub>ASQ</sub>, with a slightly different name (“strong  $A_\infty$  weights”), and with a different but equivalent definition. One of the basic observations was the following.

**B.19.4. Lemma:** Suppose that  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  is quasisymmetric and  $\mu$  is a measure on  $\mathbb{R}^n$  which satisfies (19.1). Then  $\mu$  is a metric doubling measure.

This is an easy consequence of the definitions, with  $\delta(x, y) = |f(x) - f(y)|$ .

So a necessary condition for (19.1) to hold is that  $\mu$  be a metric doubling measure. When  $n = 1$  this does not contain information beyond the requirement that  $\mu$  be doubling, because every doubling measure on the line is a metric doubling measure. (Take  $\delta(x, y) = \mu([x, y])$ .) When  $n > 1$  the metric doubling condition does contain nontrivial information.

**B.19.5. Theorem:** *If  $\mu$  is a metric doubling measure on  $\mathbb{R}^n$ ,  $n > 1$ , then  $\mu$  is an  $A_\infty$  measure on  $\mathbb{R}^n$ .*

This is another observation from [Dav–Sem]<sub>ASQ</sub>. More precisely, in [Dav–Sem]<sub>ASQ</sub> it is observed that Theorem 19.5 can be proved in the same manner as Gehring proved Theorem 18.1. This is not hard to understand. In the argument outlined in Section 18, we never really needed the mapping, just the measure. The key point is to have a version of (18.4), which should say that if  $Q$  is a cube in  $\mathbb{R}^n$  and  $\sigma$  is a line segment which connects opposite faces of  $Q$ , then the “length” of  $\sigma$  defined with respect to the quasimetric  $D(x, y)$  associated to  $\mu$  is bounded from below by a constant times the diameter of  $Q$  with respect to  $D(x, y)$ . This turns out to be true, because of the metric doubling measure condition. In order to be able to compute everything in a reasonable way, it is better to be able to assume that  $\mu$  has a density which is positive and continuous, but it turns out to be easy to reduce to that case by an approximation argument. (See [Sem]<sub>Bil</sub> for details.)

In view of Theorem 19.5 we have to ask ourselves whether every metric doubling measure on  $\mathbb{R}^n$  is associated to a quasisymmetric mapping as in (19.1). Let us first try to understand what (19.1) means. Let  $\mu$  be a metric doubling measure on  $\mathbb{R}^n$ , and suppose that  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  is quasisymmetric and satisfies (19.1). Then  $f$  defines a bi-Lipschitz mapping from  $(\mathbb{R}^n, D(x, y))$  to  $(\mathbb{R}^n, |x - y|)$ , where  $D(x, y)$  is the quasimetric associated to  $\mu$  as in Definition 19.2. This bi-Lipschitzness is not hard to verify using the definitions. (For this we only need (19.1) applied to balls rather than general subsets  $E$  of  $\mathbb{R}^n$ .)

Conversely, suppose that  $f$  is a bi-Lipschitz mapping from  $(\mathbb{R}^n, D(x, y))$  to  $(\mathbb{R}^n, |x - y|)$ . Then  $f$  is quasisymmetric with respect to the Euclidean metric, because of Proposition 4.6 and the fact that the composition of quasisymmetric mappings is quasisymmetric. One can then show that (19.1) must hold for balls. Once one has that one can deduce (19.1) for general Borel sets.

Thus the existence of a quasisymmetric mapping associated to  $\mu$  is equivalent to the bi-Lipschitz equivalence of  $(\mathbb{R}^n, D(x, y))$  and  $(\mathbb{R}^n, |x - y|)$ .

Are these spaces always bi-Lipschitz equivalent? What are the potential obstructions? We should start by asking whether  $(\mathbb{R}^n, D(x, y))$  is

Ahlfors regular of dimension  $n$ , but it is, as discussed in Section 4. Next we could ask whether a ball in  $(\mathbb{R}^n, D(x, y))$  is approximately a topological ball, in the sense that it is contained in a topological ball which is contained in a metric ball whose radius is larger than the original one by only a bounded factor. This is true, as one can see using Proposition 4.6. Are points in  $(\mathbb{R}^n, D(x, y))$  connected by curves of length comparable to their  $D(\cdot, \cdot)$ -distance? True again, a consequence of (17.5), as discussed in [Dav–Sem]<sub>ASQ</sub>, [Sem]<sub>Bil</sub>. More subtle potential obstruction: if a bi-Lipschitz mapping exists, then one should have roughly the same Sobolev and Poincaré inequalities for  $(\mathbb{R}^n, D(x, y))$  as for ordinary Euclidean space. Also true, by [Dav–Sem]<sub>ASQ</sub>. (See also [Sem]<sub>Rmks</sub>.)

So maybe it is true that  $(\mathbb{R}^n, D(x, y))$  is always bi-Lipschitz equivalent to  $(\mathbb{R}^n, |x - y|)$  when  $\mu$  is a metric doubling measure. As mentioned in Section 17, the  $A_\infty$  condition implies that for each ball  $B$  in  $\mathbb{R}^n$  the identity mapping scaled by an appropriate constant dilation gives a uniformly bi-Lipschitz mapping from  $D(x, y)$  to  $|x - y|$  on a subset of  $B$  containing 90% of its points. So simply the identity provides bi-Lipschitz mappings on large pieces of  $(\mathbb{R}^n, D(x, y))$ , and maybe one can combine them somehow to get a bi-Lipschitz mapping on the whole space.

This turns out to be wrong, starting in dimension 3 anyway. The counterexample is of the form  $\mu = \text{dist}(x, A)^N dx$ , where  $A$  is an Antoine's necklace and  $N$  is sufficiently large. Antoine's necklaces are self-similar Cantor sets which have the property that their complement in  $\mathbb{R}^n$  is not simply-connected. If one embeds a Cantor set into  $\mathbb{R}^n$  in the usual way the complement is simply-connected, but this embedding is not standard. Instead of iterating the rule that a segment is replaced by a disjoint union of segments, or similarly with cubes, Antione's necklaces are obtained by iterating the rule that a solid torus is replaced by a necklace of disjoint solid tori which link. Antione showed that the complement of such a set has nontrivial fundamental group. By taking  $N$  large, though, one can arrange it so that this set is very small in  $(\mathbb{R}^n, D(x, y))$ , e.g., that it has Hausdorff dimension as small as you like. (One can arrange it so that for each integer  $k > 0$  we can cover  $A$  by at most  $100^k$  balls with respect to  $D(\cdot, \cdot)$  each of whose radius is  $\leq \epsilon^k$ , where  $\epsilon > 0$  can be taken as small as we like by taking  $N$  large enough.) If  $(\mathbb{R}^n, D(x, y))$  were bi-Lipschitz equivalent to  $(\mathbb{R}^n, |x - y|)$ , then the image of  $A$  in the target space would be a compact subset of  $\mathbb{R}^n$  whose complement is not simply-connected and which is very small with respect to the Euclidean metric, i.e., has Hausdorff dimension as small as we like. This contradicts well-known results about general position in Euclidean spaces. By taking  $N$  as large as we like, we can even get that there is no homeomorphism from  $(\mathbb{R}^n, D(x, y))$  to  $(\mathbb{R}^n, |x - y|)$  which

is locally Hölder continuous of a positive exponent given in advance. See [Sem]<sub>BP</sub> for details.

The problem is unsolved when  $n = 2$ . Compare also with Question 16.3.

The spaces considered in this section are always quasisymmetrically equivalent to standard Euclidean spaces, but there are examples in [Sem]<sub>Good</sub> of very nice spaces which have most of the same properties as above but which do not admit quasisymmetric parameterizations. These examples begin in dimension 3, in dimension 2 there is a positive result based on the uniformization theorem. See [Sem]<sub>SC2</sub>, [Dav–Sem]<sub>QR</sub>, and [Hein–Kosk]<sub>DQC</sub>.

I suspect that it should be possible to show that the difficulties in building bi-Lipschitz mappings in dimensions  $> 1$  and quasisymmetric mappings in dimensions  $> 2$  follow from the fact that one cannot build isometries in general in dimensions  $> 1$  (no arclength parameterization) and that one cannot build conformal mappings in general in dimensions  $> 2$  (the failure of the uniformization theorem), but I do not know how to turn this principle into a precise theorem.

## B.20. Bi-Lipschitz embeddings.

Under what conditions is a metric space  $(M, d(x, y))$  bi-Lipschitz equivalent to a subset of some  $\mathbb{R}^N$ ? Or quasisymmetrically equivalent?

We can always embed a metric space isometrically into a Banach space, into the space of bounded continuous functions on  $M$ . But what if we want to land in a finite dimensional space?

It is not hard to see that it is necessary for  $M$  to be doubling in order for this to occur. This follows from Corollary 2.5 and the fact that bi-Lipschitz and quasisymmetric equivalence preserve the doubling property.

Is the converse true? Consider the following result of Assouad ([Assou]<sub>EM</sub>, [Assou]<sub>DM</sub>, [Assou]<sub>PL</sub>).

**B.20.1. Theorem:** *If  $(M, d(x, y))$  is doubling, then for each  $0 < s < 1$  there is an  $N = N(s)$  such that  $(M, d(x, y)^s)$  is bi-Lipschitz equivalent to a subset of  $\mathbb{R}^N$ .*

This is pretty good. It settles the question of quasisymmetric equivalence, and gives some information about metric spaces in general, namely that snowflakes are always okay.

The snowflake functor can destroy a lot of the most interesting aspects of the geometry of a metric space. We discussed this in Section 12, in the context of the rigidity properties of Lipschitz mappings. It also destroys the existence of curves of finite length.

We have seen before that it is much easier to build Hölder continuous

mappings with prescribed behavior at various scales and locations than Lipschitz mappings. In order to build a bi-Lipschitz embedding of an arbitrary metric space  $(M, d(x, y))$  which is doubling we would have to confront this problem.

It turns out that the answer to the question is no, that there are metric spaces which are doubling that do not admit bi-Lipschitz embeddings into finite-dimensional Euclidean spaces. The examples are based on the Heisenberg group and were known to Assouad. Recall that the Heisenberg group was defined in Section 2 and given a certain metric which is doubling. As mentioned in Section 12, Pansu [Pan]CC proved that Lipschitz functions from the Heisenberg group into the real line have the property that they have a derivative at Lebesgue-almost every point which is a group homomorphism. This fact obviously extends to Lipschitz mappings into any  $\mathbb{R}^N$ . The key point now is that any group homomorphism from the Heisenberg group into  $\mathbb{R}^N$  has to have a large kernel, the commutator subgroup, which has dimension 1 in this case. If the mapping were bi-Lipschitz, then the limiting mapping obtained by blowing up would also be bi-Lipschitz, and injective in particular. This gives a contradiction.

Let us consider a more special case. Suppose that  $\mu$  is a doubling measure on  $\mathbb{R}^n$ , and let  $D(x, y)$  be the quasimetric defined as in (3.6) with  $\alpha = 1/n$ . Can we embed  $(\mathbb{R}^n, D(x, y))$  bi-Lipschitzly into some  $\mathbb{R}^N$ ?

There is an obvious necessary condition, which is that  $\mu$  be a metric doubling measure (Definition 19.2).

One might hope that the answer for metric doubling measures is yes, since we saw in the previous section that for them  $(\mathbb{R}^n, D(x, y))$  is very close to the standard  $\mathbb{R}^n$  in its geometry, but in fact this is not true.

**B.20.2. Proposition:** *If  $(M, d(x, y))$  is any metric space which is doubling, then we can find a positive integer  $n$  and a metric doubling measure  $\mu$  on  $\mathbb{R}^n$  such that  $(M, d(x, y))$  is bi-Lipschitz equivalent to a subset of  $(\mathbb{R}^n, D(x, y))$ , where  $D(x, y)$  is associated to  $\mu$  as in (3.6), with  $\alpha = 1/n$ .*

Thus the question of bi-Lipschitz embeddability for doubling metric spaces in general is equivalent to the question for the spaces that arise from deforming Euclidean spaces using metric doubling measures.

Proposition 20.2 is proved in [Sem]BP. The construction is quite simple. Let  $(M, d(x, y))$  be given. Using Assouad's theorem we can make  $(M, d(x, y)^{1/2})$  be bi-Lipschitz equivalent to a subset  $E$  of some  $\mathbb{R}^n$ . On this  $\mathbb{R}^n$  we take  $\mu$  to be defined by  $\mu = \text{dist}(x, E)^n dx$ . One has to check that this works, but the argument is pretty straightforward.

In [Sem]Bil it is shown that  $(\mathbb{R}^n, D(x, y))$  does admit a bi-Lipschitz embedding into some  $\mathbb{R}^N$  for “most” metric doubling measures. The precise

condition is a technical, but it says that a bi-Lipschitz embedding exists when there is another metric doubling measure which is a little bit smaller than the given one in a certain sense. In the proof the embedding is constructed in a sequence of layers, where the layers come from an analysis like the Calderón-Zygmund approximation described in Section 39 below. The extra hypothesis on the metric doubling measure ensures that this infinite family of layers can be combined successfully.

One does have bi-Lipschitz embeddability for the examples based on Antoine's necklaces discussed in the preceding section.

### B.21. $A_1$ weights.

**B.21.1. Definition:** Let  $\omega(x)$  be a positive locally integrable function on  $\mathbb{R}^n$ . We say that  $\omega$  is an  $A_1$  weight if there exists a constant  $C > 0$  such that

$$\frac{1}{|B|} \int_B \omega(x) dx \leq C \operatorname{essinf}_{y \in B} \omega(y) \quad (\text{B.21.2})$$

for all balls  $B$  in  $\mathbb{R}^n$ . Here “essinf” denotes the essential infimum (where one compensates for sets of measure zero).

This is another reverse Hölder inequality, as in (17.5) and (18.6). It turns out that  $A_1$  weights are always  $A_\infty$  weights, but the reverse is very much not true. For instance,  $\omega(x) = |x|^a$  is an  $A_\infty$  weight as soon as  $a > -n$  (which is needed for local integrability), but to get an  $A_1$  weight we have to have  $-n < a \leq 0$ . The point is that  $A_1$  weights are not permitted to vanish in a nontrivial way.

If  $\omega$  is an  $A_1$  weight and  $\mu = \omega(x) dx$ , then  $\mu$  is a metric doubling measure. This is not hard to check. (See [Sem]Bil.)

Roughly speaking,  $A_1$  weights are just like  $A_\infty$  weights, except that they have only a large part, not a small part. This is made precise by the factorization theorem of Peter Jones, which characterizes  $A_\infty$  weights as the product of an  $A_1$  weight and a negative power of an  $A_1$  weight (a large part and a small part). See [Garn], [Jour], [Stein]<sub>HA</sub> for more information, and about how  $A_1$  weights can be constructed.

The examples of metric doubling measures which did not correspond to mappings in the two previous sections came from  $A_\infty$  weights that were not  $A_1$  weights. In both cases the weights had to vanish somewhere, they were positive powers of the distance to a nonempty set. Thus we have the following open problem: If  $\omega$  is an  $A_1$  weight on  $\mathbb{R}^n$ ,  $\mu = \omega(x) dx$ , and  $D(x, y)$  is the quasimetric associated to  $\mu$  as in (3.6) with  $\alpha = 1/n$ , is it true that  $(\mathbb{R}^n, D(x, y))$  is bi-Lipschitz equivalent to  $(\mathbb{R}^n, |x - y|)$ ?

It is known that the  $A_1$  condition is sufficient to ensure bi-Lipschitz embeddability into some  $\mathbb{R}^N$ . (See [Sem]<sub>Bil.</sub>)

### B.22. Interlude: bi-Lipschitz mappings between Cantor sets.

So far Cantor sets have been the least rich in structure for us. What about bi-Lipschitz mappings between them?

Let  $F_2$  and  $F_3$  be sets with 2 and 3 elements (respectively), and define  $F_2^\infty$  and  $F_3^\infty$  as in Section 2. Define metrics  $\rho_2(x, y)$  and  $\rho_3(x, y)$  on  $F_2^\infty$  and  $F_3^\infty$  as in (2.10), with  $a = 1/2$  in the case of  $F_2^\infty$  and  $a = 1/3$  in the case of  $F_3^\infty$ . This gives a pair of metric spaces, each Ahlfors regular of dimension 1, as in Section 3. Are they bi-Lipschitz equivalent?

The fact that they are both Ahlfors regular with the same dimension implies that they have roughly the same properties in terms of sizes and coverings. Since they are so disconnected one might think that it should be easy to make them bi-Lipschitz equivalent, by sliding pieces around. Remember that Cantor sets are all homeomorphic, and so it seems plausible that one could make the homeomorphisms bi-Lipschitz when the sizes match up.

This turns out to be wrong. See [Fal–Mar], [Co–Pign].

### B.23. Another moment of reflection.

We are repeatedly running into situations where we can say that the existence of a mapping implies the presence of some geometric structure, but we do not know how to go backwards and produce a mapping given some geometry. In some cases we know that this is impossible. In general, it is not easy to find homeomorphic parameterizations of spaces, or to find interesting homeomorphisms, bi-Lipschitz mappings, or quasisymmetric mappings. That is to actually obtain them under reasonable circumstances, rather than just making special examples to illustrate a point. It is easier to build interesting spaces. (See also [Sem]<sub>Map</sub>.) Interesting measures are still easier to make. (See also [Sem]<sub>Quasi</sub>.)

We turn now to the problem of finding structure in spaces even when we cannot get well-behaved homeomorphic parameterizations.

### B.24. Rectifiability.

We began Section III. with the fact that Lipschitz functions are differentiable almost everywhere. Now we want to look at this issue in the context of geometry, in which functions are replaced by sets, derivatives are replaced by tangent planes, and so forth. General references for this section include [Fal], [Fed]<sub>GMT</sub>, [Mattila].

To begin we need the notion of Hausdorff measure. We shall work always in a Euclidean space  $\mathbb{R}^n$  in this section. Given  $s \geq 0$ , a subset  $A$  of  $\mathbb{R}^n$ , and a  $\delta > 0$ , set

$$H_\delta^s(A) = \inf \left\{ \sum_j (\text{diam } E_j)^s : \{E_j\} \text{ is a sequence of sets in } \mathbb{R}^n \text{ which} \right.$$

covers  $A$  and satisfies  $\text{diam } E_j < \delta$  (B.24.1)

for all  $j \}$ , (B.24.2)

and then define the  $s$ -dimensional Hausdorff measure of  $A$  by

$$H^s(A) = \lim_{\delta \rightarrow 0} H_\delta^s(A). \quad (\text{B.24.3})$$

This limit always exists because  $H_\delta^s(A)$  is monotone in  $\delta$ , but the limit might be infinite. If  $s$  is an integer and  $A$  lies on a nice submanifold of  $\mathbb{R}^n$  of dimension  $s$ , then  $H^s(A)$  coincides with the usual surface measure of  $A$ , except perhaps for a normalizing factor. In particular we recapture Lebesgue measure when  $s = n$ . In general  $H^s$  is a countably subadditive outer measure which restricts to a countably additive measure on its collection of measurable subsets, and the Borel sets are measurable for all the Hausdorff measures.

Fix an integer  $d$ ,  $0 < d < n$ . Let us call a subset  $E$  of  $\mathbb{R}^n$  *rectifiable* if we can write  $E$  as  $E = (\bigcup_i E_i) \cup N$ , where  $\{E_i\}$  is a sequence of subsets of  $\mathbb{R}^n$  which are each bi-Lipschitz equivalent to a subset of  $\mathbb{R}^d$ , and where  $H^d(N) = 0$ . This notion of rectifiability depends very much on the choice of  $d$ , and we should mention  $d$  explicitly if there is any doubt. The reader should beware of the different uses of this terminology, “countable rectifiability” would be the name in [Fed]<sub>GMT</sub>, another name still in [Fal].

What does the concept of rectifiability really mean? One can think of it as a counterpart for sets of the concept of differentiability almost everywhere for functions. It is a way of saying that at almost all points the set behaves well, almost like a Euclidean space.

Before we get too far into that aspect of rectifiability, let us back up and consider some more basic matters of definition. Suppose that we take the same definition as above except that we replace the requirement that the  $E_i$ 's be bi-Lipschitz equivalent to subsets of  $\mathbb{R}^d$  with the requirement that they be subsets of  $C^1$  submanifolds (of dimension  $d$ ) of  $\mathbb{R}^n$ . Then we would get an equivalent definition. That may seem surprising, since  $C^1$  mappings are much nicer than Lipschitz mappings, but the point is in the measure theory, and in the differentiability almost everywhere of Lipschitz mappings. To be explicit consider a Lipschitz mapping  $f : A \rightarrow \mathbb{R}^n$ , where  $A$  is a

subset of  $\mathbb{R}^d$ . We may as well assume that  $A$  is closed, because  $f$  extends to the closure of  $A$  automatically. We can also extend  $f$  to a Lipschitz mapping on all of  $\mathbb{R}^d$ . A well-known consequence of the differentiability almost everywhere of Lipschitz mappings is that for each  $\epsilon > 0$  there is a  $C^1$  mapping  $g : \mathbb{R}^d \rightarrow \mathbb{R}^n$  which equals  $f$  everywhere except on a set of measure  $< \epsilon$ . (See [Fed]<sub>GMT</sub>.) This is how one can get  $C^1$  mappings into the picture. These error sets have small measure, and the notion of rectifiability is designed to be undisturbed by countable unions or bad sets of measure zero, in such a way that the error sets do not really matter in the end. Similarly the points at which the differential of  $g$  has rank less than  $d$  are potentially bad, but the image of this set under  $g$  has measure zero and so we may forget about it too. From here it is not too hard to see that we can get an equivalent concept of rectifiability if we take the definition of rectifiability above and ask instead that the  $E_i$ 's lie on  $C^1$  submanifolds.

A similar reasoning shows that we can ask only that the  $E_i$ 's be the images of subsets of  $\mathbb{R}^d$  under Lipschitz mappings (instead of bi-Lipschitz mappings).

It is not hard to believe that rectifiable sets have tangent planes almost everywhere, at least in some sense. The usual notion of tangent plane does not work here, where one takes a point  $x$  in  $E$  and asks that all points on  $E$  near  $x$  lie very close to the tangent plane, because we are allowing countable unions and arbitrary sets of measure zero.  $E$  might contain a countable dense set, for instance, or a countable dense family of little surfaces. In this measure-theoretic setting one has to work with the concept of “approximate tangent planes”, in which one demands that most points in  $E$  near  $x$  lie very close to the tangent plane, where “most” is computed in terms of Hausdorff measure. See [Fal], [Fed]<sub>GMT</sub>, and [Mattila].

Once we know that almost all points of  $E$  are contained in a countable union of  $C^1$  manifolds, it is not so surprising that approximate tangents exist almost everywhere. The main point is to be careful about the measure theory to control the way in which all these submanifolds are intersecting.

Conversely, the existence of approximate tangent planes almost everywhere implies rectifiability. One needs here much less precision than a tangent plane; cones would be fine. This corresponds again to the fact that Lipschitz functions and  $C^1$  functions are almost the same in this context.

To detect rectifiability in practice we need Federer's structure theorem. Before we get to that we need to have the notion of unrectifiability. A subset  $E$  of  $\mathbb{R}^n$  is called *totally unrectifiable* if  $H^d(E \cap R) = 0$  for all rectifiable sets  $R$ . This is equivalent to asking that  $H^d(E \cap R) = 0$  whenever  $R$  is a  $C^1$  submanifold of  $\mathbb{R}^n$ . Again the dimension  $d$  is implicit and should be used throughout, and the terminology is not universal.

A set  $E$  is automatically unrectifiable if  $H^d(E) = 0$ , but that is not much fun. In general one should think of unrectifiable sets as being very scattered or very crinkled. One can make examples from Cantor sets and snowflakes for instance.

A basic fact is that a given set  $E$  can be written as  $A \cup B$ , where  $A$  is rectifiable and  $B$  is totally unrectifiable, if  $E$  is  $H^d$ -measurable and  $H^d(E) < \infty$ . There is a very elegant proof of this fact which is well-known. Set

$$\alpha = \sup\{H^d(R) : R \subseteq E, R \text{ is rectifiable}\}. \quad (\text{B.24.4})$$

The first point is that this supremum is attained. Indeed, we can find a sequence  $\{R_j\}$  of rectifiable subsets of  $E$  such that  $H^d(R_j) \rightarrow \alpha$ , and we can take  $A = \bigcup_j R_j$ . We can take the  $R_j$ 's to be measurable also. With this choice of  $A$  we have that  $B = E \setminus A$  is totally unrectifiable, since otherwise  $B$  would have a nontrivial rectifiable piece which could be added to  $A$  to make it larger, in contradiction to the maximality of  $H^d(A)$ .

This shows that there is a perfect dichotomy between rectifiability and unrectifiability. It is particularly useful in combination with the following theorem of Federer.

**B.24.5. Theorem:** *Suppose that  $E \subseteq \mathbb{R}^n$  is  $H^d$ -measurable and  $H^d(E) < \infty$ . Then  $E$  is totally unrectifiable if and only if the projection of  $E$  onto almost every  $d$ -plane in  $\mathbb{R}^n$  has  $H^d$  measure zero.*

The Grassmann space of  $d$ -planes in  $\mathbb{R}^n$  is a smooth manifold and so there is a natural notion of subsets of measure zero in it. It is that notion that we use here.

See [Fed]<sub>GMT</sub>, [Mattila] for a proof of this theorem.

Theorem 24.4 is really great. It can be refined as follows. Given a (measurable) subset  $E$  of  $\mathbb{R}^n$ , its  $d$ -dimensional integral-geometric measure is defined in the following manner. Let  $V$  be a  $d$ -plane in  $\mathbb{R}^n$  which passes through the origin. We first compute the measure of the orthogonal projection of  $E$  onto  $V$ , counting multiplicities. We then take the average of these numbers over all  $d$ -planes  $V$ . This is the integral-geometric measure of  $E$ . If  $H^d(E) < \infty$  and  $E$  is unrectifiable, then we get 0 as the answer. If  $E$  is rectifiable, then we get back  $H^d(E)$  as the answer, modulo a normalizing factor perhaps, by a well-known theorem. (See [Fed]<sub>GMT</sub>.) Thus we conclude that if  $E$  is  $H^d$ -measurable and  $H^d(E) < \infty$ , then the integral-geometric measure of  $E$  computes the size of the rectifiable part of  $E$ .

This gives a very useful way to detect the presence of rectifiable sets, through topological information for instance. To illustrate this point, as-

sume that  $d = n - 1$  and that  $E$  is a closed set with  $H^d(E) < \infty$  which separates at least two points in its complement. Then  $E$  must have a non-trivial rectifiable part, because one can find a lot of hyperplanes onto which  $E$  has a nontrivial projection.

We have the idea that unrectifiable sets are sets which are very scattered, but Federer's Theorem 24.4 makes this precise in a very useful way.

### B.25. Uniform rectifiability.

What if we want to have some kind of theory of rectifiability which provides estimates?

We have seen that it can be very hard to find bi-Lipschitz parameterizations of actual given sets. On the other hand one can often verify the rectifiability of such a set, with Federer's Theorem 24.4 used as a key tool. But there is a big gap between knowing that a set is rectifiable and having a bi-Lipschitz parameterization for it.

Let us begin with a quantitative measure-theoretic assumption. Fix integers  $0 < d < n$ , and let us think about  $d$ -dimensional subsets of  $\mathbb{R}^n$ . A subset  $E$  of  $\mathbb{R}^n$  is said to be *(Ahlfors) regular* (with dimension  $d$ ) if it is closed and if there is a constant  $C > 0$  such that

$$C^{-1}r^d \leq H^d(E \cap B(x, r)) \leq Cr^d \quad (\text{B.25.1})$$

whenever  $x \in E$  and  $0 < r \leq \text{diam } E$ . This is equivalent to Definition 3.8. This is a necessary condition for a bi-Lipschitz parameterization by Euclidean space, but it is far from sufficient. Self-similar fractals, like Cantor sets and snowflakes, are Ahlfors regular.

Now we define uniform rectifiability, a quantitative and scale invariant version of the notion of rectifiability. A set  $E$  in  $\mathbb{R}^n$  is said to be *uniformly rectifiable* if it is Ahlfors regular of dimension  $d$ , and if there exist constants  $\theta, M > 0$  with the property that for each  $x \in E$  and  $0 < r < \text{diam } E$  we can find a subset  $A$  of  $E \cap B(x, r)$  such that

$$H^d(A) \geq \theta r^d \quad \text{and} \quad (\text{B.25.2})$$

$$A \text{ is } M\text{-bi-Lipschitz equivalent to a subset of } \mathbb{R}^d. \quad (\text{B.25.3})$$

In other words, inside of each ball centered on  $E$  we wish to have a substantial portion which is bi-Lipschitz equivalent to a subset of  $\mathbb{R}^d$ , with uniform bounds.

This is a complicated definition, let us try to understand it slowly. Think of the basic problem of deciding when a set  $E$  is itself bi-Lipschitz equivalent to  $\mathbb{R}^d$ . We have decided that this problem is practically unsolvable, and so we are asking for less, while still trying to keep as much of the same

flavor of the bi-Lipschitz parameterization as possible. If we do not ask for an actual bi-Lipschitz parameterization, then it is reasonable to ask that a substantial proportion of  $E$  admit such a parameterization. On the other hand one of the particular features of bi-Lipschitz mappings is their scale invariance, take a snapshot at any location and scale and you have the same estimates. Uniform rectifiability merges these two ideas: the idea of saying that we can find a good parameterization for most points, and the idea of having uniform bounds at all scales and locations. It is very close to the ideas of  $BMO$  and  $A_\infty$  weights.

Like the notion of rectifiability, uniform rectifiability enjoys some nice stability properties. In the definition above we permit  $\theta$  to be as small as we want, so long as it is fixed. Suppose that we prescribe a small  $\epsilon > 0$  in advance, and ask instead of (25.2) that

$$H^d((E \cap B(x, r)) \setminus A) \leq \epsilon r^d. \quad (\text{B.25.4})$$

It turns out that if we make this change then we get a condition which is equivalent to the one above. The price to pay for taking  $\epsilon$  small is to increase  $M$  in (25.3).

Regular subsets of uniformly rectifiable sets are uniformly rectifiable. The union of two uniformly rectifiable sets is uniformly rectifiable.

If we replace (25.3) with the requirement that  $A$  be the  $M$ -Lipschitz image of a subset of  $\mathbb{R}^d$  of diameter  $\leq r$ , then we also get an equivalent condition. This relies on a theorem of Peter Jones [Jones]<sub>Lip</sub>.

It turns out that if  $E$  is Ahlfors regular and is unbounded, then  $E$  is uniformly rectifiable if and only if  $E \times \mathbb{R}$  is (as a subset of  $\mathbb{R}^{n+1}$ ). (If  $E$  is bounded one should take the product with a finite interval.) This type of statement is at best unclear for the question of bi-Lipschitz parameterizations by  $\mathbb{R}^d$ .

One of the basic questions is whether one can detect uniform rectifiability under reasonable geometric conditions. The ideal would be to have something like Federer's Theorem 24.4. One would be happy to know that if a set has bounded Hausdorff measure and if there is a lower bound on the measure of its projections (counted without multiplicities) onto a large collection of  $d$ -planes, then the set has a substantial piece which is bi-Lipschitz equivalent to a subset of  $\mathbb{R}^d$ , with uniform bounds. This is a natural quantitative conjecture motivated by Federer's theorem. Unfortunately it remains unknown. There is a method of David ([David]<sub>MG</sub>, see also [David]<sub>WSI</sub>) which provides uniform rectifiability results in many of the cases in which one would like to apply a quantitative version of Federer's result, in many situations in which one has suitable "lower bounds on topology", for instance. See also [Dav-Jer], [Dav-Sem]<sub>QR</sub>, [Sem]<sub>Find</sub>, [Jon-Ka-Var], [DS5].

### B.26. Stories from the past.

One of the original motivations for studying uniform rectifiability came from analysis, namely the problem of knowing on which sets certain classes of singular integral operators were bounded on  $L^2$ . This question grew out of the Calderón program (see [Cald]), and earlier work of Calderón, Coifman, MacIntosh, Meyer, and David showed that lots of singular integral operators were bounded on sets that were bi-Lipschitz equivalent to Euclidean spaces. (See [Coif–Dav–Mey], [David]<sub>WSI</sub> for more information and further references.) Such sets have little smoothness, but they come with parameterizations, which is a lot. The question then was what kind of sets were really allowed, what kind of smoothness was needed, what kind of parameterization, and whether there were simple geometric criteria for singular integrals to be well behaved.

Much of the previous work focussed on 1-dimensional sets, in which the issue of the existence of a parameterization is much less significant, because of arclength parameterizations. In higher dimensions there is no arclength parameterization, and the relationship between geometry and parameterization is much less clear.

For one-dimensional sets the best result is due to David [David]<sub>PC</sub>, who showed that singular integral operators are well behaved on curves which are Ahlfors regular of dimension 1. He did this by proving two things: that such curves are uniformly rectifiable, and that singular integral operators are well behaved on uniformly rectifiable sets. (Actually he worked with a slightly stronger version of uniform rectifiability.) The second statement, that uniform rectifiability implies good behavior for singular integral operators, works in all dimensions. It is not immediately clear how to formulate the first statement for higher dimensional sets, because of the lack of arclength parameterizations. For one formulation, based on a kind of parameterization discussed in the next section, David proved in [David]<sub>SR</sub> that singular integral operators are well behaved, using something slightly weaker than uniform rectifiability.

A very different approach to the problem was given in [Sem]<sub>BSI</sub>. A geometric condition was given there for sets of codimension 1 to be well behaved for singular integral operators. This condition requires that the set be topologically nontrivial in a uniform way at all scales and locations, as measured by separating points in the complement. The methods used were analytical, and did not provide much insight into the geometry of the set.

The story of  $\epsilon$ -flat hypersurfaces in [Sem]<sub>SC1</sub> was also somewhat disturbing for the idea of parameterizations. Here was a class of hypersurfaces

which were much better than uniformly rectifiable but for which it was not at all clear that there was a nice global parameterization, even of the type in [David]<sub>SR</sub>.

Another disturbing fact was a criterion in [Sem]<sub>SC2</sub> for the existence of well-behaved parameterizations of 2-dimensional sets. This criterion provided the existence of a global parameterization which was strong enough to imply uniform rectifiability but which was not accommodated by the class of parameterizations permitted in the first version of [David]<sub>SR</sub> (a situation David later rectified by enlarging his class of parameterizations). This criterion had also the annoying feature that it relied on the uniformization theorem, and so gave information in a mysterious way which did not work in higher dimensions.

These were the circumstances at the time that David did [David]<sub>MG</sub>. It was not clear then that there was a common geometric thread to these examples. Something like uniform rectifiability was a clear guess, but it was not clear that one should always have it, or that it was reasonable to ask always for good parameterizations of large pieces of sets. One of the main problems was that it was not known that the sets considered in [Sem]<sub>BSI</sub> had any uniform rectifiability properties or good parameterizations. Rectifiability was clear because of Federer's structure theorem. One of the main results of [David]<sub>MGL</sub> was that these sets are uniformly rectifiable. Simpler proofs of this were given later in [Dav–Jer] and [Dav–Sem]<sub>QR</sub>, and [Sem]<sub>Rect</sub> provided an approach to the geometry of these sets through analysis.

David also showed in [David]<sub>MGL</sub> that uniform rectifiability is implied by the existence of the kind of parameterizations considered in [David]<sub>SR</sub>. He gave in addition a criterion for uniform rectifiability for sets of codimension larger than 1 analogous to the condition in [Sem]<sub>BSI</sub> in codimension 1 (in terms of uniform lower bounds on topology). No other method is known for doing this in higher codimensions. Analytical methods as in [Sem]<sub>BSI</sub> do not seem to work very well in higher codimensions.

In [Dav–Sem]<sub>SI</sub> a converse was obtained, to the effect that if you have an Ahlfors regular set on which sufficiently many singular integral operators are well behaved, then the set must be uniformly rectifiable. Some other characterizations were established, including some of the ones mentioned earlier. These results showed that there was really only one natural notion of uniform rectifiability. It was also shown that uniformly rectifiable sets are always contained in sets which admit a parameterization of the type in [David]<sub>SR</sub>.

For more information about these topics see [Dav–Sem]<sub>UR</sub> and [Sem]<sub>Find</sub>.

## B.27. Regular mappings.

**B.27.1. Definition:** Let  $(M, d(x, y))$  and  $(N, \rho(u, v))$  be metric spaces (or quasimetric spaces). We say that a mapping  $f : M \rightarrow N$  is regular if it is Lipschitz and if for each ball  $B$  in  $N$  we can cover  $f^{-1}(B)$  by at most  $C$  balls in  $M$  with the same radius as  $B$ , where  $C$  does not depend on  $B$ .

For example,  $f : \mathbb{R} \rightarrow \mathbb{R}$  defined by  $f(x) = |x|$  is regular. A bi-Lipschitz embedding is regular if  $M$  is doubling, but regular mappings need not be bi-Lipschitz. Note that a regular mapping can have only a bounded number of preimages for each point in the range.

Regular mappings provide us with a variation on the theme of what constitutes a good parameterization. Instead of asking that a set admit a bi-Lipschitz parameterization by a Euclidean space, we can ask for a regular parameterization, which allows some crossings. We could also ask that a given set be contained in a regular image of a Euclidean space, i.e., we could allow some holes, for the sake of balance.

One of the results of [David]<sub>MG</sub> is that the image of  $\mathbb{R}^d$  in any  $\mathbb{R}^n$  under a regular mapping is uniformly rectifiable. It is not known whether every uniformly rectifiable set is contained in such a regular image.

This situation provides a nice example of how metric doubling measures (Definition 19.2) can be used, as a way to perturb Euclidean geometry modestly. Let  $\mu$  be a metric doubling measure on  $\mathbb{R}^d$ , and let  $D(x, y)$  denote the associated quasidistance, as in (3.6), with  $\alpha = 1/d$ . It turns out that the image of  $(\mathbb{R}^d, D(x, y))$  in  $\mathbb{R}^n$  under a regular mapping is always uniformly rectifiable. This comes from the  $A_\infty$  property of metric doubling measures (Theorem 19.5), which helps to ensure that the geometry of  $(\mathbb{R}^d, D(x, y))$  is sufficiently close to being Euclidean. Conversely, given a uniformly rectifiable subset of  $\mathbb{R}^n$  with dimension  $d$ , then it is contained in the image of such a regular mapping for some metric doubling measure  $\mu$ . For this we need to assume that  $n$  is large enough compared to  $d$ , or we have to settle for a regular mapping into  $\mathbb{R}^{n+1}$ . See [Dav–Sem]<sub>SI</sub>.

For the converse, for the construction of a regular mapping which contains a given uniformly rectifiable set in its image, we can take the metric doubling measure  $\mu$  to be of the form  $\omega(x) dx$ , where  $\omega$  is actually an  $A_1$  weight (Definition 21.1). It remains unknown whether  $(\mathbb{R}^d, D(x, y))$  is always bi-Lipschitz equivalent to  $(\mathbb{R}^d, |x - y|)$  when the density of  $\mu$  is an  $A_1$  weight (as discussed in Section 21), and if this is true one could get rid of the weight in this story of regular mappings.

When does a metric space  $(M, d(x, y))$  admit a regular mapping into some finite dimensional Euclidean space? A necessary condition is that  $M$

$(M, d(x, y))$  which admits a regular mapping into some finite dimensional Euclidean space also admits a bi-Lipschitz embedding into some Euclidean space of larger but still finite dimension.

### B.28. Big pieces of bi-Lipschitz mappings.

**B.28.1. Theorem ([David]<sub>MG</sub>):** *Let  $Q$  denote the unit cube in  $\mathbb{R}^n$ . Suppose that  $f : Q \rightarrow \mathbb{R}^n$  is Lipschitz, and that  $|f(Q)| \geq \delta > 0$ . Then there exists an  $\epsilon > 0$  such that there is a subset  $E$  of  $Q$  with  $|E| \geq \epsilon$  such that the restriction of  $f$  to  $E$  is  $\epsilon^{-1}$ -bi-Lipschitz. This  $\epsilon$  depends only on the dimension  $n$ , the Lipschitz constant for  $f$ , and  $\delta$ , and not on the specific choice of  $f$ .*

I like this theorem very much. A crucial point is to have universal bounds.

This is not true in general for metric spaces, even under suitable measure-theoretic assumptions so that it all makes sense. It is not true for mappings on Cantor sets for instance. (David and I found counterexamples.) Another example: consider the snowflake  $([0, 1], |x - y|^{1/2})$ . A well-known construction of a space-filling curve provides a Lipschitz mapping from this space onto the unit square in  $\mathbb{R}^2$ , but no such mapping can be bi-Lipschitz on a set of positive measure. (Lipschitz and bi-Lipschitz maps from  $([0, 1], |x - y|^{1/2})$  into itself are the same as Lipschitz and bi-Lipschitz maps with respect to the Euclidean metric, so there is nothing new there.)

A third example: Start with the set  $F = \{0, 1\}$ , construct the Cantor set  $F^\infty$  of infinite sequences of elements of  $F$ , as in Section 2, and give it a metric  $d(x, y)$  as in (2.10), with  $a = 1/2$ . This defines a metric space which is Ahlfors regular of dimension 1 (Definition 3.8). There is an obvious mapping from  $F^\infty$  onto  $[0, 1]$ , obtained by taking an element of  $F$  and interpreting it as a binary sequence of a real number. This mapping is Lipschitz, and even regular, but one can show that it cannot be bi-Lipschitz on a set of positive measure.

Thus David's Theorem 28.1 again reflects rigidity properties of Lipschitz mappings on Euclidean spaces which are not true abstractly. This rigidity property has the nice feature that it is easier to formulate for general spaces (like Ahlfors regular metric spaces) than something like differentiability almost everywhere.

Theorem 28.1 is closely related to differentiability almost everywhere. This point is easier to understand in terms of the fact that for each Lipschitz mapping  $f : Q \rightarrow \mathbb{R}^n$  (where  $Q$  is still the unit cube in  $\mathbb{R}^n$ ) and every  $\delta > 0$  there is a  $C^1$  mapping  $g : Q \rightarrow \mathbb{R}^n$  which equals  $f$  except on a set of measure

mapping  $f : Q \rightarrow \mathbb{R}^n$  (where  $Q$  is still the unit cube in  $\mathbb{R}^n$ ) and every  $\delta > 0$  there is a  $C^1$  mapping  $g : Q \rightarrow \mathbb{R}^n$  which equals  $f$  except on a set of measure  $< \delta$ . Using this fact it is not hard to show that if  $f(Q)$  has positive measure, then  $f$  must be bi-Lipschitz on a set of positive measure. Indeed, this comes down to the inverse function theorem, which implies that a  $C^1$  function is bi-Lipschitz on a neighborhood of any point at which the differential is invertible, and the fact that the set of points where the differential of a  $C^1$  mapping is not invertible gets mapped to a set of measure zero in the image.

This analysis implies Theorem 28.1 but without the uniform bound on  $\epsilon$ . The remarkable feature of David's theorem is that it does provide such a bound.

Peter Jones gave the following improvement of David's theorem.

**B.28.2. Theorem ([Jones]<sub>Rec</sub>):** *Let  $Q$  denote the unit cube in  $\mathbb{R}^n$ , and let  $f : Q \rightarrow \mathbb{R}^n$  be a 1-Lipschitz mapping. Let  $\eta > 0$  be given. Then there are compact subsets  $K_1, \dots, K_N$  of  $Q$  such that the restriction of  $f$  to each  $K_j$  is  $N$ -bi-Lipschitz, and such that*

$$\left| f(Q \setminus \bigcup_{i=1}^N K_i) \right| < \eta. \quad (\text{B.28.3})$$

Here  $N$  depends only on the dimension  $n$  and on  $\eta$ .

In other words, we can break up the domain  $Q$  into a bounded number of pieces, in such a way that one of these pieces has a small image, and the restriction of  $f$  to each of the others is bi-Lipschitz. As an illustration think about the mapping  $z \mapsto z^k$  on the unit disk in  $\mathbb{C}$ . Note that the Lipschitz norm of this mapping is  $k$ .

If we did not want to have a bound on the number of pieces  $K_i$ , then Theorem 28.2 would not be so exciting. It would follow from much simpler arguments, about approximating Lipschitz functions by  $C^1$  functions.

Although we do not know much about building bi-Lipschitz parameterizations of whole spaces, there is some pretty good technology for finding bi-Lipschitz mappings on sets of a definite size. This is one of the reasons why the notion of uniform rectifiability works well.

One of the main points in Jones' proof is to have some quantitative understanding of how often Lipschitz functions are well approximated by affine functions. We shall take a closer look at this topic in the next section. For now let us just say that a key feature of affine functions is that if you control their Lipschitz norm, and if you know that they do not shrink volumes too much, then you can control their bi-Lipschitz constant. Jones

combines this trivial observation with the good approximations of Lipschitz functions by affine functions and a coding argument to prove his Theorem 28.2. (See Section 43 for slightly more information.)

Jones' argument also works when the target space is  $\mathbb{R}^m$  and  $m > n$ , but then one must be careful about the kind of “measure” to use in (28.3) (Hausdorff content instead of Hausdorff measure).

See [Dav–Sem]<sub>QR</sub> for some variations on these themes.

### B.29. Quantitative smoothness for Lipschitz functions.

How smooth are Lipschitz functions on Euclidean spaces? We know that they are differentiable almost everywhere, but can we say more than that? Can we say something quantitative? The Lipschitz condition is a quantitative condition; it is not nice to have differentiability almost everywhere but not a quantitative statement. One has a bound on the size of the derivative, but what about some kind of bound on the “differentiability”, on the extent to which Lipschitz functions are approximately affine?

What kind of quantitative statement might we be able to hope for? We cannot hope for bounds on the rate of convergence of the limit in the derivative.

Let  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  be given, and consider the quantity

$$\alpha(x, t) = t^{-1} \inf \left\{ \sup_{y \in B(x, t)} |f(y) - a(y)| : a \text{ is an affine function} \right\}. \quad (\text{B.29.1})$$

Here  $x \in \mathbb{R}^n$  and  $t > 0$ , and  $\alpha(x, t)$  provides a measure of the oscillation of  $f$  on the ball  $B(x, t)$ . It measures the extent to which the snapshot of  $f$  on  $B(x, t)$  is almost affine. The normalization here – dividing by  $t$  – is the natural one for taking the snapshot of a Lipschitz function, just like in the definition of the derivative. With this normalization  $\alpha(x, t)$  is always bounded by the Lipschitz norm of  $f$  (just take  $a(y)$  to be the constant function  $f(x)$ ). The question is whether  $\alpha(x, t)$  is small as a dimensionless quantity.

If  $f$  is differentiable at a point  $x$ , then

$$\lim_{t \rightarrow 0} \alpha(x, t) = 0. \quad (\text{B.29.2})$$

The vanishing of this limit is not equivalent to the existence of a derivative. If  $\alpha(x, t)$  is small, then  $f$  is well-approximated by an affine function on  $B(x, t)$ , but this affine function can spin around as  $t \rightarrow 0$ . The existence of a derivative means that (29.2) holds and that these affine approximations do not spin around, that in fact a single affine function works well for all (small)  $t$ .

If  $f$  is Lipschitz, then what can we say about the  $\alpha(x, t)$ 's? How often are they small? We know that (29.2) must hold for almost all  $x$ , but can we do better than this? Can we get a bound for the number of times that the  $\alpha(x, t)$ 's are not small? It turns out that we can do this, but to do this properly we need a new concept, the concept of Carleson sets. Before we get to that let us make some more naive observations.

The  $\alpha(x, t)$ 's fit well with our idea of snapshots of a function — they are measuring the size of the oscillations of these snapshots. Our collection of snapshots is parameterized by  $\mathbb{R}^n \times \mathbb{R}_+$ , where  $\mathbb{R}_+$  denotes the set of positive real numbers. That is,  $\mathbb{R}^n \times \mathbb{R}_+$  parameterizes the space of balls in  $\mathbb{R}^n$ , and we have a snapshot of  $f$  for each ball.

In Section 1 we saw how hyperbolic geometry on  $\mathbb{R}^n \times \mathbb{R}_+$  can be natural in analysis, and this is one of those occasions. In this case this means that  $\alpha(x, t)$  does not change a whole lot when we move  $(x, t)$  by a modest amount in the hyperbolic metric. Actually, for our purposes of getting bounds on  $\alpha(x, t)$ , it is a little better to use an observation that does not quite fit as well with the idea of hyperbolic geometry. Namely, given  $x, y \in \mathbb{R}^n$  and  $s, t \in \mathbb{R}_+$ , we have that

$$\alpha(y, s) \leq 4\alpha(x, 2t) \quad \text{whenever } |x - y| \leq t \text{ and } \frac{t}{2} \leq s \leq t. \quad (\text{B.29.3})$$

This is not hard to check from the definitions, the main point being that  $B(y, s) \subseteq B(x, 2t)$  under the assumptions above. This observation says that if  $\alpha(x, 2t)$  is small for some  $(x, t)$ , then  $\alpha(y, s)$  is small for a lot of  $(y, s)$  which are close to  $(x, t)$  hyperbolically. The extra factor of 2 in front of the  $t$  is a little unpleasant for crisp geometric statements, but this observation implies nonetheless that we have to respect hyperbolic geometry on  $\mathbb{R}^n \times \mathbb{R}_+$  to some extent when we try to understand how often the  $\alpha(x, t)$ 's are small. We should not expect anything too interesting to happen to  $\alpha(x, t)$  at small distances in the hyperbolic metric. We should instead look at large hyperbolic distances. For instance, (29.3) implies that if (29.2) holds, so that  $\alpha(x, t)$  is small for  $(x, t)$  on a small vertical ray (i.e., for  $x$  fixed and all small  $t > 0$ ), then  $\alpha(y, s)$  is automatically small for all  $(y, s)$  in a cone around that ray (a uniform hyperbolic neighborhood of the ray).

Carleson sets provide a useful notion of “small” subsets of  $\mathbb{R}^n \times \mathbb{R}_+$ . A measurable subset  $\mathcal{A}$  of  $\mathbb{R}^n \times \mathbb{R}_+$  is said to be a *Carleson set* if there is a constant  $C > 0$  such that

$$\int_0^t \int_{B(x, t)} \mathbf{1}_{\mathcal{A}}(y, s) \frac{dy ds}{s} \leq C t^n \quad (\text{B.29.4})$$

for all  $x \in \mathbb{R}^n$  and  $t \in \mathbb{R}_+$ . Here  $\mathbf{1}_{\mathcal{A}}(y, s)$  denotes the characteristic function of  $\mathcal{A}$ . This condition is a mouthful, let us take it slowly.

We are integrating over the region  $B(x, t) \times (0, t)$  in  $\mathbb{R}^n \times \mathbb{R}_+$ . If we think of  $\mathbb{R}^n \times \mathbb{R}_+$  as parameterizing the locations and scales in  $\mathbb{R}^n$ , then  $B(x, t) \times (0, t)$  parameterizes the locations and scales near  $x$  and finer than  $t$ . In practice we shall look at sets  $\mathcal{A}$  like

$$\{(x, t) \in \mathbb{R}^n \times \mathbb{R}_+ : \alpha(x, t) > \epsilon\}, \quad (\text{B.29.5})$$

for fixed  $\epsilon > 0$ . In this case the membership of  $(x, t)$  in  $\mathcal{A}$  depends only on the values of  $f$  in  $B(x, t)$ . The integral in (29.4) depends only on the values of  $f$  in  $B(x, 2t)$ . This integral measures the total oscillations of  $f$  at all scales and locations inside  $B(x, 2t)$ .

If the integrand  $\mathbf{1}_{\mathcal{A}}(y, s)$  were not present in (29.4), then the integral would diverge, because of the  $ds/s$  integral. Indeed,

$$\int_a^b \int_{B(x,t)} \frac{dy ds}{s} = c(n) t^n \log \frac{b}{a}, \quad (\text{B.29.6})$$

where  $c(n)$  is in fact the volume of the unit ball in  $\mathbb{R}^n$ . This is why the Carleson condition is a smallness condition. Already the convergence of the integral in (29.4) implies that  $\mathcal{A}$  is small in a nontrivial way.

Here is a basic example. Suppose that  $F$  is a subset of the integers, and set

$$\mathcal{A} = \{(x, t) \in \mathbb{R}^n \times \mathbb{R}_+ : 2^j < t < 2^{j+1} \text{ for some } j \in F\}. \quad (\text{B.29.7})$$

Then  $\mathcal{A}$  is a Carleson set if and only if  $F$  is finite, and in this case the Carleson constant (the best constant  $C$  for (29.4)) is proportional to the number of elements of  $F$ .

The Carleson condition (29.4) is a way of trying to count the average number of layers in  $\mathcal{A}$ . Fix  $\mathcal{A}$  and  $t > 0$ , and set

$$N_t(y) = \int_0^t \mathbf{1}_{\mathcal{A}}(y, s) \frac{ds}{s}. \quad (\text{B.29.8})$$

This tries to count the number of layers in  $\mathcal{A}$  directly above  $y$  up to the level  $t$ . The  $ds/s$  in the integral is natural here, natural for the hyperbolic geometry, a “layer” should be something like  $[s, 2s]$  for some  $s > 0$ . Different layers in  $\mathbb{R}^n \times \mathbb{R}_+$  correspond to different scales in  $\mathbb{R}^n$ . We can rewrite (29.4) as

$$t^{-n} \int_{B(x,t)} N_t(y) dy \leq C. \quad (\text{B.29.9})$$

In other words the average of  $N_t(y)$  over  $B(x, t)$  should be bounded.

If  $\mathcal{A}$  is as in (29.5), and  $f$  is Lipschitz, then (29.2) holds almost everywhere. This implies that  $N_t(y) < \infty$  almost everywhere. If  $\mathcal{A}$  is a Carleson set, then one gets much more than  $N_t < \infty$  a.e.

**B.29.10. Theorem:** *If  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is Lipschitz and  $\epsilon > 0$  is arbitrary, then (29.5) defines a Carleson set, with a Carleson constant bounded by a constant that depends only on  $n$ ,  $\epsilon$ , and the Lipschitz constant of  $f$ .*

This is a very interesting fact. I am not sure exactly how to attribute it. Jones [Jones]<sub>Lip</sub> was the first person that I know to explicitly state and use it. Results roughly like this have been stated before – it is easy to derive Theorem 29.10 from [Dorr] – but [Jones]<sub>Lip</sub> is the first place where I saw this kind of fact used in a meaningful way, to prove Theorem 28.2.

Let us consider some more examples. Let  $H$  be a hyperplane in  $\mathbb{R}^n$ , and set  $f(x) = \text{dist}(x, H)$ . Notice that  $f$  is affine on each of the two complementary components of  $H$ . This implies that

$$\alpha(x, t) = 0 \quad \text{when } \text{dist}(x, H) \geq t, \quad (\text{B.29.11})$$

where  $\alpha(x, t)$  is again as in (29.1). If we take  $\mathcal{A}$  to be as in (29.5) (for some  $\epsilon > 0$ ), then

$$\mathcal{A} \subseteq \{(x, t) \in \mathbb{R}^n \times \mathbb{R}_+ : \text{dist}(x, H) < t\}. \quad (\text{B.29.12})$$

It is not hard to check directly that the right hand side is a Carleson set. In this case the multiplicity functions  $N_t(x)$  are not bounded, but we do have the average bounds (29.9). Indeed,  $N_t(x) = 0$  when  $\text{dist}(x, H) \geq t$ , and when  $\text{dist}(x, H) < t$ , we have that  $N_t(x)$  is roughly like  $\log(t/\text{dist}(x, H))$ .

A more elaborate example to consider is  $f(x) = \text{dist}(x, E)$ , where  $E$  is any subset of  $\mathbb{R}^n$ . We might as well take  $E$  to be closed. This gives a 1-Lipschitz function on  $\mathbb{R}^n$  which can be a little more complicated for the  $\alpha(x, t)$ 's, and I do not think that Theorem 29.10 is so trivial in this case. A relevant Carleson set for this example is

$$\{(x, t) \in \mathbb{R}^n \times \mathbb{R}_+ : \text{dist}(x, E) < t < 2 \text{dist}(x, E)\}. \quad (\text{B.29.13})$$

For this set, the functions  $N_t(x)$  are all bounded, and the set has only one “layer”, but it is not at a uniform height. The Carleson constant does not depend on the choice of  $E$ .

As another illustration of Theorem 29.10 let us consider the following consequence of it. Suppose that  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is Lipschitz with norm 1, say,

and let  $\epsilon > 0$  be given. Then there is a constant  $k$  which depends only on  $\epsilon$  and  $n$  so that for any ball  $B(x, t)$  in  $\mathbb{R}^n$ , there is a ball  $B(y, s) \subseteq B(x, t)$  such that  $s \geq t/k$  and  $\alpha(y, s) < \epsilon$  ( $f$  is almost affine on  $B(y, s)$ ). On average we should expect that there are plenty of balls  $B(y, s)$  like this, but even in the worst case there is always one which is not too different from  $B(x, t)$ . It is not hard to derive this from Theorem 29.10, using (29.6), for instance. This fact is slightly crude compared to the whole truth, but it provides a nice manifestation of the uniform and scale-invariant nature of the smoothness of Lipschitz functions.

If a function on  $\mathbb{R}^n$  satisfies the conclusions of Theorem 29.10, to what extent must it be like a Lipschitz function? Not so much, as in the next example. Define  $f : \mathbb{R} \rightarrow \mathbb{R}$  by

$$f(x) = \sum_{j=1}^{\infty} a_j 2^{-j} \exp(2^j i x), \quad (\text{B.29.14})$$

where  $\{a_j\}$  is a bounded sequence of numbers. (Back to lacunary series, as in Section 12.) One can compute that

$$\lim_{t \rightarrow 0} \sup_{x \in \mathbb{R}^n} \alpha(x, t) = 0 \quad \text{if } \lim_{j \rightarrow \infty} a_j = 0, \quad (\text{B.29.15})$$

where  $\alpha(x, t)$  is as in (29.1). Also, this function  $f$  is bounded, and we have that

$$\alpha(x, t) \leq t^{-1} \|f\|_{\infty}, \quad (\text{B.29.16})$$

whence  $\lim_{t \rightarrow \infty} \sup_{x \in \mathbb{R}^n} \alpha(x, t) = 0$ . Therefore  $\lim_{j \rightarrow \infty} a_j = 0$  implies that for each  $\epsilon > 0$  there exist  $\delta, R > 0$  such that

$$\alpha(x, t) > \epsilon \quad \text{implies} \quad \delta < t < R. \quad (\text{B.29.17})$$

In this case the conclusions of Theorem 29.10 certainly hold, because the  $N_t$ 's are all uniformly bounded (for a fixed  $\epsilon$ ). On the other hand, in order for the distributional derivative of  $f$  to lie in  $L^2_{loc}(\mathbb{R})$  it is necessary for  $\sum_j |a_j|^2 < \infty$ . This follows from basic facts about Fourier series. By taking sequences  $\{a_j\}$  which tend to 0 but which are not square summable we can get functions which satisfy the conclusion of Theorem 29.10 very well but which are badly behaved in terms of differentiability properties. In fact more refined results from harmonic analysis imply that in this case  $f'$  will not look like a function in any reasonable sense, not just that it will not be in  $L^2_{loc}(\mathbb{R})$ .

So we cannot really characterize anything like the Lipschitz property in terms of the conclusions of Theorem 29.10. To get such a characterization

we have to impose stronger conditions. There are basically two reasonable ways to do that. The first is to impose stronger conditions on the size of the  $\alpha(x, t)$ 's. We shall not enter into the details, but Theorem 29.10 is a reduction of a better estimate on quantities like the  $\alpha(x, t)$ 's, and the reduction is like Chebychev's theorem (controlling the measure of a set where a function is large rather than the integral). The better estimate can be derived from [Dorr], and involves  $L^2$  integrals. The second reasonable way to strengthen the conclusion of Theorem 29.10 is to impose conditions on how fast the good affine approximations to  $f$  spin around. This second approach is based on Carleson's corona construction, and is exposed in Chapter 2 of Part IV of [Dav–Sem]<sub>UR</sub>. Actually, these strengthenings of the conclusion of Theorem 29.10 do not capture quite the Lipschitz property of a function, but are better adapted to something like functions whose gradient lies in  $BMO$ . This is not a catastrophic difference though.

So why should we expect any kind of good estimates for the  $\alpha(x, t)$ 's at all? Why should we expect them to be small most of the time, when the Lipschitz condition doesn't seem to say much more than their boundedness? All the good estimates that I know come down to some kind of orthogonality, e.g., Plancherel's theorem asserting that the Fourier transform preserves the  $L^2$  norm, or estimates derived from some other Hilbert space consideration. Let us consider functions on the real line, specifically a function  $f$  in  $L^2$  of the real line. It is well known that  $f' \in L^2(\mathbb{R})$  if and only if

$$\sup_{t>0} \int_{\mathbb{R}} \left| \frac{f(x+t) - f(x)}{t} \right|^2 dx < \infty. \quad (\text{B.29.18})$$

In this case

$$\frac{f(x+t) - f(x)}{t} \rightarrow f'(x) \quad \text{as } t \rightarrow 0 \quad (\text{B.29.19})$$

in  $L^2$ . On the other hand  $f' \in L^2(\mathbb{R})$  if and only if

$$\int_0^\infty \int_{\mathbb{R}} \left| \frac{f(x+t) + f(x-t) - 2f(x)}{t} \right|^2 \frac{dx dt}{t} < \infty. \quad (\text{B.29.20})$$

This is not too hard to verify, using the Fourier transform. Plancherel's theorem transforms the  $x$ -integral into an integral on the Fourier side, and then the  $t$ -integral splits off. The conclusion is that the double integral in (29.20) is equal to a constant multiple of  $\int |f'|^2$ .

Let us compare (29.20) and (29.18). We are interested in the quantities

$$\int_{\mathbb{R}} \left| \frac{f(x+t) - f(x)}{t} \right|^2 dx \quad \text{and} \quad \int_{\mathbb{R}} \left| \frac{f(x+t) + f(x-t) - 2f(x)}{t} \right|^2 dx, \quad (\text{B.29.21})$$

as functions of  $t$ . The first is bounded as a function of  $t$  in the situation of interest, and we cannot say more as  $t \rightarrow 0$  because (29.19) ensures that it tends to a nonzero limit when  $f$  is not constant. The second quantity is also bounded but in fact it does tend to 0 as  $t \rightarrow 0$  when  $f' \in L^2$ . It has to be small most of the time in order for the double integral in (29.20) to be finite, because the  $dt/t$  gives infinite measure to  $(0, 1)$ . A bound on (29.20) gives a bound on how often it is small, on average.

The second difference  $f(x+t) + f(x-t) - 2f(x)$  is closely related to  $\alpha(x, t)$ . If  $\alpha(x, t) = 0$ , then  $f$  equals an affine function on  $B(x, t)$ , and hence the second difference  $f(x+t) + f(x-t) - 2f(x)$  vanishes. One cannot control  $\alpha(x, t)$  directly in terms of  $f(x+t) + f(x-t) - 2f(x)$ , but one can control  $\alpha(x, t)$  in terms of averages of second differences.

As a practical matter there are more convenient ways to control the  $\alpha(x, t)$ 's than using second differences, but the principles remain the same. One first controls some quantities that measure the oscillation of functions using the Fourier transform or other orthogonality methods, and then one controls the  $\alpha(x, t)$ 's in terms of averages of these quantities.

Although Theorem 29.10 does not provide the definitive information about the smoothness of Lipschitz functions, it does provide nontrivial information that is useful for geometry. The  $\alpha(x, t)$ 's are better for geometry than other common measurements of oscillation in analysis, and simply the knowledge that they are smaller than a small threshold is often more useful than more subtle measurements of their size. Theorem 29.10 is pretty sharp for its formulation. Practically all Carleson sets arise in this manner (although it would be easier to allow functions  $f$  with  $\nabla f \in BMO$  instead of just Lipschitz functions).

See [Dav–Sem]<sub>QR</sub>, [Dav–Sem]<sub>UR</sub> for variations on the theme of Theorem 29.10.

### B.30. Smoothness of uniformly rectifiable sets.

How smooth are uniformly rectifiable sets? The short answer is that they are practically as smooth as Lipschitz functions, with the “smoothness” of Lipschitz functions interpreted as in the preceding section. There is a particularly nice formulation of this statement which corresponds to Theorem 29.10, which we shall discuss now.

Let integers  $0 < d < n$  be given, and let  $E$  be a  $d$ -dimensional Ahlfors regular set in  $\mathbb{R}^n$  (as in (25.1)). The concept of Carleson sets in  $E \times \mathbb{R}_+$  can be formulated in exactly the same manner as before, with  $E$  playing the role of  $\mathbb{R}^n$ , and with the restriction of Hausdorff measure  $H^d$  to  $E$  playing the role of Lebesgue measure on  $\mathbb{R}^n$ . Ahlfors regularity ensures that Carleson

sets behave in the same way as on Euclidean spaces.

How do we measure the smoothness of a set? For functions we like to measure the extent to which they are well-approximated by affine functions, while for sets we like to measure the extent to which they are well-approximated by planes. Given  $x \in E$  and  $t > 0$  set

$$b\beta(x, t) = \inf_P \left\{ t^{-1} \sup_{y \in E \cap B(x, t)} \text{dist}(y, P) + t^{-1} \sup_{z \in P \cap B(x, t)} \text{dist}(z, E) \right\}. \quad (\text{B.30.1})$$

The “b” here stands for “bilateral”, and the  $\beta$  was inherited from Peter Jones [Jones]<sub>Squ</sub>, [Jones]<sub>Rec</sub>. The infimum in (30.1) is taken over all  $d$ -planes  $P$ , and  $b\beta(x, t)$  measures the extent to which  $E$  is approximately equal to a  $d$ -plane in  $B(x, t)$ . Note that  $b\beta(x, t) = 0$  if and only if  $E$  coincides with a  $d$ -plane inside  $B(x, t)$ . The factor of  $t^{-1}$  is a useful normalization which ensures that  $b\beta(x, t) \leq 1$ .  $b\beta(x, t)$  is a dimensionless quantity.

We say that  $E$  satisfies the “Bilateral Weak Geometric Lemma (BWGL)” if

$$\{(x, t) \in E \times \mathbb{R}_+ : b\beta(x, t) > \epsilon\} \quad (\text{B.30.2})$$

is a Carleson set inside  $E \times \mathbb{R}_+$  for each  $\epsilon > 0$ . (Compare with (29.5).)

**B.30.3. Theorem:** *A regular set  $E$  is uniformly rectifiable (Section 25) if and only if it satisfies the BWGL.*

This is proved in [Dav–Sem]<sub>UR</sub> (Theorem 2.4 in Part I).

The fact that uniform rectifiability implies the BWGL can be seen as a geometric version of Theorem 29.10. The converse, the fact that the BWGL implies uniform rectifiability, can be seen as the geometric analogue of false statements about functions. We saw in the previous section how the conclusions of Theorem 29.10 do not come too close to capturing the Lipschitzness of a function, and it is amusing that when we switch to geometry this problem goes away. This phenomenon can be better understood in terms of a “unilateral” version of  $b\beta(x, t)$ , namely

$$\beta(x, t) = \inf_P \left\{ t^{-1} \sup_{y \in E \cap B(x, t)} \text{dist}(y, P) \right\}. \quad (\text{B.30.4})$$

Here again the infimum is taken over all  $d$ -planes. This quantity measures the extent to which  $E$  lies close to a  $d$ -plane inside  $B(x, t)$ , but it does not require that points in  $B(x, t)$  which lie on the  $d$ -plane also lie close to  $E$ . Holes are allowed. Thus  $\beta(x, t) = 0$  means that  $E \cap B(x, t)$  lies on a  $d$ -plane,

but it need not coincide with the intersection of  $B(x, t)$  with the  $d$ -plane. If we ask that

$$\{(x, t) \in E \times \mathbb{R}_+ : \beta(x, t) > \epsilon\} \quad (\text{B.30.5})$$

be a Carleson set inside  $E \times \mathbb{R}_+$  for each  $\epsilon > 0$ , then we get a condition called the Weak Geometric Lemma (WGL) which is necessary but not sufficient for uniform rectifiability. (See [Dav–Sem]<sub>SI</sub> for an example.) If we want to characterize rectifiability properties of sets in terms of the size of the  $\beta(x, t)$ , then we have to work with stronger quadratic Carleson measure estimates, as in [Jones]<sub>S<sub>qu</sub></sub>, [Jones]<sub>R<sub>ec</sub></sub>, and [Dav–Sem]<sub>SI</sub>, and this fact is completely analogous to the relevant quadratic estimates for the  $\alpha(x, t)$ 's for functions in [Dorr], [Jones]<sub>S<sub>qu</sub></sub>. When we work with the  $b\beta(x, t)$ 's we get a different phenomenon, and the analogy with functions breaks down. See [Dav–Sem]<sub>UR</sub>.

The distinction between  $\beta(x, t)$  and  $b\beta(x, t)$  does not have an obvious counterpart in the context of functions.

The BWGL says that a uniformly rectifiable set looks like a  $d$ -plane at most scales and locations. One cannot really do much better than say that the set of exceptions is a Carleson set. There are seemingly stronger properties that uniformly rectifiable sets enjoy, including one modeled on Carleson's corona construction which controls how fast the approximating  $d$ -planes spin around. (See [Sem]<sub>Rect</sub>, [Dav–Sem]<sub>SI</sub>, [Dav–Sem]<sub>UR</sub>.)

One can try to detect the rectifiability properties of sets by measuring approximations against other sets of models besides  $d$ -planes. This issue arises in connection with various problems in analysis and is taken up in [Dav–Sem]<sub>UR</sub>. Reasonable sets of models include convex sets, connected sets, Lipschitz graphs, minimal surfaces, and sets whose complementary components are convex. There is a much larger variety of reasonable models to consider in geometry than in linear analysis.

### B.31. Comments about geometric complexity.

How can one control the geometric complexity of a set in  $\mathbb{R}^n$ , or of a metric space?

If one has a specific model in mind, like Euclidean space, it is reasonable to ask first for controlled parameterizations. We have seen some limitations to this approach. Even in the best situations in topology – compact smooth manifolds or piecewise-linear manifolds – one always has problems with complexity which stem from the fundamental group (perhaps local fundamental groups).

So we give up on parameterizations, what next then? Uniform rectifiability provides one answer. It captures pretty much all the “smoothness”

that a set should have if it were to have a bi-Lipschitz parameterization, capturing this smoothness in a more flexible way that is much easier to detect. Measurements of smoothness like the bilateral weak geometric lemma (BWGL) and the corona decomposition discussed in Section 30 are very suggestive of certain types of constructions, in which one says that the geometry of the set is usually very tame, the number of times that it is bad can be controlled in terms of a Carleson set, and ad hoc arguments in the bad cases give some good control overall. There are plenty of examples where this type of argument works pretty well. (See  $[\text{Sem}]_{\text{Rect}}$ ,  $[\text{Dav-Sem}]_{SI}$ ,  $[\text{Dav-Sem}]_{UR}$ .) Nonetheless this type of approach clearly misses a lot. Uniform rectifiability does not do such a good job of capturing information that is more topological in nature. Perhaps it could be combined with topological information in a more productive way. One can view  $[\text{Dav-Sem}]_{ASQ}$ ,  $[\text{Sem}]_{Diff}$ ,  $[\text{Sem}]_{QT}$ ,  $[\text{Sem}]_{Rmks}$  as providing some alternate approaches to controlling the geometric complexity of spaces which are roughly Euclidean but maybe not parameterized well.

This issue of geometric complexity is fundamentally not understood. It is not at all clear even what language to use. In this appendix we have seen some examples, but still the basic perspectives rest on a lot of assumptions.

## IV. An introduction to real-variable methods

In this last part we describe some basic techniques from harmonic analysis and we indicate some of the arguments needed for statements mentioned earlier. These real-variable methods reflect the interaction between measure theory and the geometry of snapshots.

### B.32. The Maximal function.

Let  $(M, d(x, y), \mu)$  be a space of homogeneous type, as in Section 8. For simplicity one can just think about Euclidean spaces with the usual metric and Lebesgue measure. At any rate we ask that  $d(x, y)$  be an actual metric, instead of a quasimetric, but this is only for convenience and entails no loss of generality because of (2.2).

Given a locally integrable function  $f$  on  $M$ , define the (*Hardy-Littlewood*) maximal function  $f^*$  of  $f$  by

$$f^*(x) = \sup_{B \ni x} \frac{1}{\mu(B)} \int_B |f(y)| d\mu(y). \quad (\text{B.32.1})$$

The supremum here is taken over all (open) balls  $B$  which contain  $x$ . Some-

times people prefer to use the “centered” maximal function, given by

$$\sup_{r>0} \frac{1}{\mu(B(x,r))} \int_{B(x,r)} |f(y)| d\mu(y). \quad (\text{B.32.2})$$

This is no greater than  $f^*(x)$ , and  $f^*(x)$  is bounded by a constant multiple of the centered maximal function, because of the doubling condition on  $\mu$ . Thus the two are practically equivalent, but the uncentered version is a little nicer for geometric interpretation.

Maximal functions arise very naturally in analysis, for proving theorems about the existence almost everywhere of limits and for controlling singular integral operators. One can appreciate them at a more naive level by thinking about trying to control the snapshots of a function in terms of simpler information (like integrability).

When I first saw the definition of the maximal function as a student I was impressed by its brashness. It seems to be asking a lot to expect that  $f^*$  be finite in nontrivial situations, to take the supremum over *all* balls that way. Nonetheless it works out well.

**B.32.3. Theorem:** *Notation and assumptions as above. If  $f \in L^1(\mu)$  then we have the “weak type” inequality*

$$\mu(\{x \in M : f^*(x) > \lambda\}) \leq C \lambda^{-1} \|f\|_1 \quad (\text{B.32.4})$$

for some constant  $C$  (which depends only on the doubling constant for  $\mu$ ) and all  $\lambda > 0$ . If  $f \in L^p(\mu)$  for some  $p > 1$ , then  $f^* \in L^p$  and

$$\|f^*\|_p \leq C(p) \|f\|_p, \quad (\text{B.32.5})$$

where  $C$  depends only on  $p$  and the doubling constant for  $\mu$ .

This theorem probably looks strange if one is not accustomed to these things, so let us take it slowly. To understand the weak-type inequality it is helpful to look at an example. Actually, let us agree to extend the definition of the maximal function to locally finite measures in the obvious manner. If we do that, and if we take  $(M, d(x,y), \mu)$  to be the real line equipped with Lebesgue measure, then the maximal function of a Dirac mass at the origin is the function given by  $1/|x|$ . This is not integrable near the origin or at infinity. This is why  $f \mapsto f^*$  cannot be bounded on  $L^1$ , or even take  $L^1$  into itself. Strictly speaking measures are not the same as  $L^1$  functions, but in any concrete situation like this you cannot have good behavior on  $L^1$  while having such bad behavior for measures. This fact can be made precise by building  $L^1$  functions that contain little copies of approximate Dirac masses, and then showing that the maximal function has suitably bad behavior.

However this example is perfectly compatible with the weak-type inequality (32.4), and it shows that the weak-type inequality is optimal in a natural way.

Note that the weak-type inequality would hold automatically if the  $L^1$  norm of  $f^*$  were controlled by the  $L^1$  norm of  $f$ . The weak-type inequality is what we would get from the  $L^1$  bound using Chebychev's inequality.

The weak-type inequality also works for finite measures, and with the same proof, which we give in the next section.

What about the other  $L^p$  spaces? The  $L^\infty$  estimate is trivial and not very useful. The  $L^p$  estimates are more remarkable for being able to take the supremum in (32.1) inside the integral. For  $1 < p < \infty$  it turns out that there is a general “interpolation” theorem due to Marcinkiewicz which permits one to obtain the  $L^p$  bounds from the  $L^1$  and  $L^\infty$  estimates. Note that we have less than boundedness at  $L^1$  but we are recapturing boundedness in between. See [Stein]<sub>SI</sub>, [Stein]<sub>HA</sub>, and [Stein–Weiss] for more details. The penalty for the unboundedness at  $p = 1$  is that the constants  $C(p)$  in (32.5) blow up as  $p \rightarrow 1$ , at a rate like  $(p - 1)^{-1}$ .

This phenomenon occurs repeatedly in analysis, that one has bounds for  $1 < p < \infty$  but not at the endpoints. Here  $p = \infty$  is trivially okay, but normally it is not, as in the context of singular integral operators. For linear operators the  $p = 1$  and  $p = \infty$  cases correspond to each other under duality.

For our purposes it is the weak-type inequality for  $L^1$  that matters most, and not so much the  $L^p$  estimates which are very important in analysis in general.

An amusing fact: if  $f$  is a locally integrable function with  $f^* \not\equiv \infty$  and if  $0 < \delta < 1$ , then  $(f^*)^\delta$  is an  $A_1$  weight (Definition 21.1), and one can get all  $A_1$  weights in this manner, modulo multiplication by functions that are bounded and bounded away from 0. This was proved by Coifman and Rochberg. See [Garn], [Jour], [Stein]<sub>HA</sub>.

### B.33. Covering lemmas.

Again let  $(M, d(x, y), \mu)$  be a space of homogeneous type, with  $d(x, y)$  an actual metric for simplicity. Suppose that  $f \in L^1(\mu)$ , and set

$$E_\lambda = \{x \in M : f^*(x) > \lambda\}, \quad (\text{B.33.1})$$

where  $\lambda > 0$  is given. Notice that  $E_\lambda$  is an *open* set. We want to control  $\mu(E_\lambda)$ .

What do we know about  $E_\lambda$ ? If  $x \in E_\lambda$ , then there is a ball  $B$  such

that  $x \in B$  and

$$\frac{1}{\mu(B)} \int_B |f(y)| d\mu(y) > \lambda. \quad (\text{B.33.2})$$

Thus  $E_\lambda$  is covered by balls of this type. In order to control  $\mu(E_\lambda)$  we need a covering lemma, and the following works.

**B.33.3. Lemma:** *Let  $(M, d(x, y))$  be a metric space, and let  $\mathcal{B}$  be a collection of balls (open or closed) of bounded radius which covers a set  $E$ . Then we may extract from  $\mathcal{B}$  a sequence of pairwise disjoint balls  $\{B_i\}$ , possibly finite, such that either*

$$E \subseteq \bigcup_i 5B_i \quad (\text{B.33.4})$$

*or there are infinitely many  $B_i$ 's and they all have radii uniformly bounded away from 0.*

This is well known, and the argument on p. 9-10 of [Stein]<sub>SI</sub> works, for instance. The idea is easy enough. One chooses  $B_1$  in  $\mathcal{B}$  so that its radius is as large as possible, to within a factor of 2, and then one chooses the  $B_i$ 's recursively so that at each stage the new ball is disjoint from its predecessors and with radius as large as possible, to within a factor of 2. One then checks that either the radii tend to 0, in which case one gets the covering property (33.4), or they remain bounded away from 0. This proves the lemma.

Let us now use this to prove that

$$\mu(E_\lambda) \leq C \lambda^{-1} \int_M |f(y)| d\mu(y). \quad (\text{B.33.5})$$

To avoid a small technical problem let  $F$  be an arbitrary bounded (measurable) subset of  $E_\lambda$ , and let us get an estimate for  $\mu(F)$  which does not depend on the choice of  $F$ . Let  $\mathcal{B}$  be the set of balls which satisfy (33.2), and let  $\mathcal{B}_F$  denote the elements of  $\mathcal{B}$  which intersect  $F$ . We claim that there is a sequence of pairwise disjoint balls  $\{B_i\}$  in  $\mathcal{B}_F$  such that

$$\mu(F) \leq \sum_i \mu(5B_i). \quad (\text{B.33.6})$$

This basically follows from the lemma, but with a couple of small qualifications. If the balls in  $\mathcal{B}_F$  do not have bounded radii, then we just take one very large ball  $B_1$  in  $\mathcal{B}_F$ , and that will satisfy  $F \subseteq 5B_1$ . If the balls in  $\mathcal{B}_F$  do have bounded radii, then we may apply Lemma 33.3. Either we get the covering property (33.4), in which case we are in business, or there are

infinitely many  $B_i$ 's and their radii are bounded away from 0. In this case the right side of (33.6) is infinite, because of the doubling property for  $\mu$ , and because all the  $B_i$ 's intersect the bounded set  $F$  by assumption.

Because the  $B_i$ 's are disjoint and satisfy (33.2) we have that

$$\begin{aligned} \mu(F) &\leq \sum_i \mu(5B_i) \leq C \sum_i \mu(B_i) \\ &\leq C \sum_i \lambda^{-1} \int_{B_i} |f(y)| d\mu(y) \quad (\text{B.33.7}) \\ &\leq C \lambda^{-1} \int_M |f(y)| d\mu(y). \end{aligned}$$

This constant  $C$  depends on the doubling constant for  $\mu$  and on nothing else. Since  $F$  is an arbitrary bounded subset of  $E_\lambda$  we conclude that

$$\mu(E_\lambda) \leq C \lambda^{-1} \int_M |f(y)| d\mu(y), \quad (\text{B.33.8})$$

as desired.

This completes the proof of the weak-type inequality (32.4) in Theorem 32.3.

On the real line there is a very special covering lemma. Given any three intervals which contain a point in common, one of the intervals is contained in the union of the other two. This is easy to check. It implies that if a compact set  $K$  in  $\mathbb{R}$  is covered by a family of open intervals, then one can cover  $K$  by finitely many of these intervals, and with the additional restriction that no point in  $\mathbb{R}$  is contained in more than two of the intervals. This fact leads to another development of the weak-type inequality on the real line.

## B.34. Lebesgue points.

**B.34.1. Theorem:** *Let  $(M, d(x, y), \mu)$  be a space of homogeneous type, with  $d(x, y)$  a metric (rather than a quasimetric) for convenience. If  $f \in L^1_{loc}(\mu)$ , then*

$$\lim_{r \rightarrow 0} \frac{1}{\mu(B(x, r))} \int_{B(x, r)} |f(y) - f(x)| d\mu(y) = 0 \quad (\text{B.34.2})$$

for  $\mu$ -almost all  $x \in M$ .

To prove this we may as well assume that  $f \in L^1$  since the matter is entirely local. Set

$$\Lambda(f)(x) = \limsup_{r \rightarrow 0} \frac{1}{\mu(B(x, r))} \int_{B(x, r)} |f(y) - f(x)| d\mu(y). \quad (\text{B.34.3})$$

That is,  $\Lambda$  is a (nonlinear) operator which takes locally integrable functions to measurable functions. We want to show that  $\Lambda(f) \equiv 0$   $\mu$ -a.e. for all  $f \in L^1(\mu)$ .

The operator  $\Lambda$  has three important features. The first is that it is sublinear, which means that

$$\Lambda(f_1 + f_2) \leq \Lambda(f_1) + \Lambda(f_2) \quad (\text{B.34.4})$$

for all  $f_1, f_2 \in L^1$ . This is easy to check. The second is that

$$\Lambda(g) \equiv 0 \quad (\text{B.34.5})$$

when  $g$  is continuous, by definitions. The third is that

$$\Lambda(f) \leq 2 f^*. \quad (\text{B.34.6})$$

Thus we have a bound on the size of  $\Lambda(f)$  coming from (32.4).

Every  $f \in L^1$  can be approximated by continuous functions. That is, for each  $\epsilon > 0$  there is a continuous function  $g$  on  $M$  such that

$$\int_M |f(z) - g(z)| d\mu(z) < \epsilon. \quad (\text{B.34.7})$$

(This uses the Borel regularity of  $\mu$ .) From the sublinearity property (34.4) and (34.5) we have that

$$\Lambda(f) = \Lambda(f - g). \quad (\text{B.34.8})$$

Using these two facts together with (34.6) and (32.4) we obtain that

$$\{x \in M : \Lambda(f)(x) > t\} \leq C t^{-1} \epsilon \quad (\text{B.34.9})$$

for some  $C > 0$  and all  $t > 0$ ,  $\epsilon > 0$ . We have applied (32.4) here with  $f$  replaced by  $f - g$ , and it is important that  $C$  does not depend on either  $t$  or  $\epsilon$ . Since  $\epsilon > 0$  is arbitrary we have that

$$\{x \in M : \Lambda(f)(x) > t\} = 0 \quad (\text{B.34.10})$$

for all  $t > 0$ , and hence that  $\Lambda(f) \equiv 0$  almost everywhere. This proves the theorem.

The proof of this theorem indicates a very general recipe for establishing the existence of limits almost everywhere. The main point is to have a maximal function estimate like (32.4). In the presence of such a bound the existence of limits almost everywhere can be derived from the existence of limits for a dense class, which is typically much easier to get.

### B.35. Differentiability almost everywhere.

Let us now specialize to the case of  $\mathbb{R}^n$  and look at another question of the existence of limits, namely differentiability almost everywhere for Lipschitz functions. We are going to prove Theorem 12.1 using an argument like the one in the previous section.

Roughly speaking, the functions in the previous section correspond to the derivatives of the functions that we shall consider in this section. Note well that we shall use a lot of structure of Euclidean spaces here that does not work on spaces of homogeneous type except in very special situations (like the Heisenberg group).

As in the preceding section we need to have a maximal function to work with. In the present case it is given by

$$N(f)(x) = \sup_{r>0} r^{-1} \sup_{y \in B(x,r)} |f(y) - f(x)|. \quad (\text{B.35.1})$$

This function measures the oscillations of  $f$  near  $x$  with the same scaling as the derivative. We want to get a bound for this operator, and then use it to establish the existence almost everywhere of the derivative of a Lipschitz function.

If  $f$  is Lipschitz, then  $N(f)$  is uniformly bounded. This is a bound, but it is not a useful one. In order to get differentiability almost everywhere we need to understand the behavior of limits for a dense class. We would like to use smooth functions for our dense class, but they are not dense in the space of Lipschitz functions with respect to the Lipschitz norm. We have to use a weaker norm. The same issue is implicit in the preceding section; continuous functions are not dense in  $L^\infty$  with respect to the  $L^\infty$  norm, but they are dense in  $L^p$  when  $p < \infty$ .

The first thing that we need to do here is to get our hands on some  $L^\infty$  functions so that we can drop down to  $L^p$  spaces. For that matter we have to produce a candidate for the derivative, which is not given to us a priori.

For this we use the notion of weak derivatives. Given two locally integrable functions  $f$  and  $g$  on  $\mathbb{R}^n$ , we say that  $g = \frac{\partial}{\partial x_j} f$  in the weak sense if

$$\int_{\mathbb{R}^n} f(x) \frac{\partial}{\partial x_j} \phi(x) dx = - \int_{\mathbb{R}^n} g(x) \phi(x) dx \quad (\text{B.35.2})$$

for all smooth functions  $\phi$  on  $\mathbb{R}^n$  with compact support. This amounts to saying that  $g = \frac{\partial}{\partial x_j} f$  “in the sense of distributions”. Note that (35.2) holds when  $f$  is continuously differentiable and we use its ordinary derivative.

**B.35.3. Lemma:** *If  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is Lipschitz, then for each  $j = 1, 2, \dots, n$  there is a function  $g_j \in L^\infty(\mathbb{R}^n)$  such that  $g_j = \frac{\partial}{\partial x_j} f$  in the weak sense.*

This is well known, but let us sketch the argument. Let  $e_j$  denote the standard basis vector in  $\mathbb{R}^n$  in the direction of  $x_j$ , and consider the quantity

$$F_j(x, h) = \frac{f(x + h e_j) - f(x)}{h} \quad (\text{B.35.4})$$

for  $h \in \mathbb{R}$ . We would like to take a limit of this as  $h \rightarrow 0$ . A priori we do not know that this limit exists, only that these functions are uniformly bounded in  $L^\infty$ . Standard results in functional analysis imply that we can find a sequence  $\{h_k\}$  of real numbers which tend to 0 such that  $F_j(x, h_k)$  converges to a function  $g_j \in L^\infty$ , where the convergence is in the sense of the *weak\** topology on  $L^\infty$  with respect to the duality with  $L^1$ . As a practical matter this means that

$$\lim_{k \rightarrow \infty} \int_{\mathbb{R}^n} F_j(x, h_k) \phi(x) dx = \int_{\mathbb{R}^n} g_j(x) \phi(x) dx \quad (\text{B.35.5})$$

for all  $\phi \in L^1$ . The key point behind this existence result is to realize the limiting object initially as an element of the dual space of  $L^1$ , and not directly as an  $L^\infty$  function. One first obtains the existence of the limit on the left side of (35.5) for a countable dense collection of  $\phi$ 's, using a diagonalization argument to choose the sequence  $\{h_k\}$  correctly, and then one shows that the limit exists as an element of the dual space, etc.

Once one has  $g_j$  as in (35.5), it is easy to check that  $g_j = \frac{\partial}{\partial x_j} f$  in the weak sense. This proves the lemma.

The derivative in the weak sense (35.2) is unique if it exists. This is amusing in the context of the preceding proof, for which it implies that the *weak\** limit  $g_j$  does not really depend on the choice of  $\{h_k\}$ . In fact one can conclude that  $\lim_{h \rightarrow 0} F_j(x, h) = g_j(x)$ , where again the convergence is taken in the *weak\** topology.

How exactly can we use this notion of weak derivative in concrete terms? The answer lies in regularization, the process by which we take a function on  $\mathbb{R}^n$  which is not smooth and approximate it by a smooth function. Regularization through convolution, as follows. Let  $\theta$  be a smooth function on  $\mathbb{R}^n$  which vanishes outside the unit ball and which satisfies  $\int_{\mathbb{R}^n} \theta(x) dx = 1$ . Set  $\theta_t(x) = t^{-n} \theta(x/t)$ , so that  $\theta_t$  is supported in  $B(0, t)$  and also has  $\int_{\mathbb{R}^n} \theta_t(x) dx = 1$ . Convolution of  $f$  with  $\theta_t$  is given by

$$f * \theta_t(x) = \int_{\mathbb{R}^n} f(y) \theta_t(x - y) dy. \quad (\text{B.35.6})$$

Thus  $f * \theta_t(x)$  is really an average of values of  $f$  near  $x$ , “near” meaning points in  $B(x, t)$ .

The main points now are these. We have that

$$\lim_{t \rightarrow 0} f * \theta_t = f \quad (\text{B.35.7})$$

uniformly when  $f$  is uniformly continuous, in particular when  $f$  is Lipschitz. This is easy to verify directly. If  $h(x) \in L^p_{loc}$ ,  $1 \leq p < \infty$ , then

$$\lim_{t \rightarrow 0} h * \theta_t = h \quad (\text{B.35.8})$$

in  $L^p_{loc}$ . This is a standard fact and also not difficult to prove. The version for  $L^p_{loc}$  follows easily from the version for  $L^p$  because the problem is local. For  $L^p$  we use the fact that continuous functions with compact support are dense to reduce to (35.7). This requires also the simple fact that  $h \mapsto h * \theta_t$  is a uniformly bounded family of linear operators on each  $L^p$  space.

For any locally integrable function  $f$  we have that  $f * \theta_t$  is smooth. This follows from (35.6) and the smoothness of  $\theta$ . Suppose we know also that  $\frac{\partial}{\partial x_j} f$  exists as a locally integrable function in the weak sense described above. Then

$$\frac{\partial}{\partial x_j} (f * \theta_t) = \left( \frac{\partial}{\partial x_j} f \right) * \theta_t. \quad (\text{B.35.9})$$

This is a nice exercise, using (35.6) and (35.2).

Let us summarize our conclusions in the following lemma.

**B.35.10. Lemma:** *Let  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  be Lipschitz. Then there is a family of smooth functions  $f_t : \mathbb{R}^n \rightarrow \mathbb{R}$ ,  $t > 0$ , such that  $f_t \rightarrow f$  uniformly as  $t \rightarrow 0$  and  $\frac{\partial}{\partial x_j} f_t \rightarrow \frac{\partial}{\partial x_j} f$  in  $L^p_{loc}(\mathbb{R}^n)$  for each  $p < \infty$ . Here  $\frac{\partial}{\partial x_j} f$  is taken in the weak sense (35.2). If  $f$  has compact support, then we have convergence in  $L^p$  and not just  $L^p_{loc}$ .*

For the convergence of the derivative we combine (35.9) with (35.8).

This lemma tells us that we can approximate Lipschitz functions by smooth functions in a nice way. (We could easily derive additional information, such as the uniform boundedness of  $\frac{\partial}{\partial x_j} f_t$ .) Next we want a maximal function estimate.

**B.35.11. Theorem:** *Suppose that  $g$  is a smooth function on  $\mathbb{R}^n$  with  $\nabla g \in L^p(\mathbb{R}^n)$  for some  $n < p \leq \infty$ . Then*

$$\|N(g)\|_p \leq C(p, n) \|\nabla g\|_p, \quad (\text{B.35.12})$$

where  $C(p)$  does not depend on  $g$ .

Remember that  $N(\cdot)$  is defined in (35.1).

The restriction  $p > n$  is sharp when  $n > 1$ , and it reflects the famous Sobolev embedding theorem. This point is more prominent in the following lemma.

**B.35.13. Lemma:** *Let  $B$  be an open ball in  $\mathbb{R}^n$  and let  $g$  be a smooth function on  $B$ . Then*

$$|g(z) - g_B| \leq C \int_B \frac{1}{|u - z|^{n-1}} |\nabla g(u)| du \quad (\text{B.35.14})$$

for all  $z \in B$ , where  $g_B$  denotes the average of  $g$  over  $B$ . This constant  $C$  depends only on the dimension  $n$ .

The proof will show that  $g$  is integrable on  $B$  as soon as the right side is finite.

When  $n = 1$  one can reduce (35.14) to the fundamental theorem of calculus using Fubini's theorem, and when  $n > 1$  we do the same except we must average over paths in all directions. Specifically, if  $w \in B$ , then

$$|g(z) - g(w)| \leq \int_0^1 |\nabla g((1-s)z + sw)| ds, \quad (\text{B.35.15})$$

by the fundamental theorem of calculus. To get (35.14) one simply averages this over  $w$ . One can compute that the right side of (35.14) comes out, and we leave this as an exercise. (Reduce to  $z = 0$  and then make a change the variables  $u = sw$ .) This proves the lemma.

Let us convert this inequality into a more directly useful form.

**B.35.16. Lemma:** *Let  $B$  be an open ball in  $\mathbb{R}^n$  with radius  $r > 0$  and let  $g$  be a smooth function on  $B$ . If  $n < q \leq \infty$  ( $q = 1$  is allowed when  $n = 1$ ), then*

$$r^{-1} \sup_{u,v \in B} |g(u) - g(v)| \leq C(q, n) \left( \frac{1}{|B|} \int_B |\nabla g(w)|^q dw \right)^{\frac{1}{q}}. \quad (\text{B.35.17})$$

This is an easy consequence of (35.14) and Hölder's inequality. The main point is that  $|x|^{1-n}$  lies in  $L_{loc}^q$  when  $q > n$  (and not in  $L_{loc}^n$  when  $n > 1$ ).

Let us prove now Theorem 35.11. Let  $n < q \leq p$  be given, with  $q = 1$  permitted when  $n = 1$ , and set  $f = |\nabla g|^q$ . Then Lemma 35.16 implies that

$$N(g)(x)^q \leq C(q, n) f^*(x) \quad (\text{B.35.18})$$

for all  $x$ . If we are careful to choose  $q < p$ , then  $f \in L^s(\mathbb{R}^n)$  with  $s = p/q > 1$ , and Theorem 32.3 implies that  $f^* \in L^s(\mathbb{R}^n)$ . The norm bound (35.12) then follows from (32.5).

Since we did not actually give a proof of (32.5) here let us observe that we can also take  $q = p$  and apply (32.4) to obtain that

$$|\{x \in \mathbb{R}^n : N(g)(x)^p > \lambda\}| \leq C(n) \lambda^{-1} \int_{\mathbb{R}^n} |\nabla g(y)|^p dy. \quad (\text{B.35.19})$$

This weaker inequality is sufficient for the present proof of Theorem 12.1.

The assumption of smoothness of  $g$  in Theorem 35.11 is made only for simplicity. It suffices to take a locally integrable function  $g$  on  $\mathbb{R}^n$  such that  $\nabla g \in L^p$  exists in the weak sense. In this case one has to accommodate the technical nuisance that  $g$  could behave badly on a set of measure zero and require modification there, but this is not a serious issue. The point is that one can approximate  $g$  by smooth functions using convolutions as above, apply Theorem 35.11 to the approximations, and then take limits.

Let us now use Theorem 35.11 to show that Lipschitz functions on  $\mathbb{R}^n$  are differentiable almost everywhere. Let  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  be Lipschitz, and assume without loss of generality that  $f$  has compact support. Fix any  $p > n$ . Let  $\{f_t\}$  be a family of smooth approximations to  $f$  as in Lemma 35.10. We want to use the differentiability of the  $f_t$ 's to derive the differentiability of  $f$ , and for this we need more information about the approximation. Let us check that

$$\lim_{t \rightarrow 0} \|N(f - f_t)\|_p = 0. \quad (\text{B.35.20})$$

Morally this follows from Theorem 35.11, but technically we have a small problem since  $f$  is not smooth. This is resolved by using Fatou's lemma to show that

$$\|N(f - f_t)\|_p \leq \liminf_{s \rightarrow 0} \|N(f_s - f_t)\|_p. \quad (\text{B.35.21})$$

From here (35.20) follows easily.

Define an operator  $L(g)$  by

$$L(g)(x) = \lim_{r \rightarrow 0} r^{-1} \sup_{y \in B(x,r)} |g(y) - g(x) - \nabla g(x) \cdot (y - x)|. \quad (\text{B.35.22})$$

To say that  $L(g)(x) = 0$  means exactly that  $g$  is differentiable at  $x$  and that its derivative is given by  $\nabla g(x)$ . We assume here that  $\nabla g$  exists in the weak sense as a locally integrable function, for instance. We want to show

that  $L(f) = 0$  almost everywhere. It is easy to see that  $L$  is sublinear, so that

$$L(f) \leq L(f - f_t) + L(f_t) \quad (\text{B.35.23})$$

for all  $t > 0$ . The smoothness of  $f_t$  implies that  $L(f_t) \equiv 0$  for all  $t > 0$ . Thus

$$L(f) \leq L(f - f_t). \quad (\text{B.35.24})$$

We also have that

$$L(g) \leq N(g) + |\nabla g| \quad (\text{B.35.25})$$

for all functions  $g$ . From (35.20) and the fact that  $\nabla f_t \rightarrow \nabla f$  in  $L^p$  norm we conclude that  $\|L(f)\|_p = 0$ , so that  $L(f) = 0$  almost everywhere.

This proves that  $f$  is differentiable almost everywhere and that its gradient is given by the gradient in the weak sense obtained before.

There is a lot more to say about functions with locally integrable derivatives in the weak sense (see [Ev–Gar], [Stein]SI), but the preceding arguments touch many of the basic techniques.

There are other reasonable ways to approach the differentiability almost everywhere of Lipschitz functions. One argument (going back to Calderón?) relies on the observation that if  $f$  is Lipschitz, then for each  $p < \infty$  we have that

$$\lim_{r \rightarrow 0} r^{-n} \int_{B(x,r)} |\nabla f(y) - \nabla f(x)|^p dy = 0 \quad (\text{B.35.26})$$

for almost all  $x \in \mathbb{R}^n$ . This uses only the fact that  $\nabla f \in L^p(\mathbb{R}^n)$ , and it can be derived from a Lebesgue point argument much like the one in the proof of Theorem 34.1. From this one can get

$$\lim_{r \rightarrow 0} r^{-1} \sup_{y \in B(x,r)} |f(y) - f(x) - \nabla f(x) \cdot (y - x)| = 0 \quad (\text{B.35.27})$$

almost everywhere using (35.17) (generalized from smooth functions to Lipschitz functions). (I learned this method from Pekka Koskela.)

### B.36. Finding Lipschitz pieces inside functions.

Let  $(M, d(x,y))$  be a metric space and let  $f : M \rightarrow \mathbb{R}$  be a function. Suppose that we are in a situation where  $f$  is not Lipschitz but we wish that it were. What to do?

We can begin by defining the function  $N(f)$  as in (35.1). This makes sense on any metric space. Let us suppose that we have some kind of control on  $N(f)$ , so that  $N(f) \neq \infty$ . We saw in the preceding section how we can sometimes control the size of  $N(f)$ , in terms of its  $L^p$  norm for instance, when we are working on a Euclidean space. There are similar results in other contexts.

Let us assume also that  $f$  is continuous, for simplicity.

Let  $\lambda > 0$  be given, and consider the set

$$F_\lambda = \{x \in M : N(f)(x) \leq \lambda\}. \quad (\text{B.36.1})$$

It is easy to see that  $F_\lambda$  is closed when  $f$  is continuous. We think of  $F_\lambda$  as being the set where  $f$  behaves like it is Lipschitz with constant  $\leq \lambda$ .

Let us assume that  $F_\lambda \neq \emptyset$  and be precise about the idea that  $f$  behaves like it is  $\lambda$ -Lipschitz on  $F_\lambda$ , even near  $F_\lambda$ . We have that

$$|f(x) - f(y)| \leq \lambda d(x, y) \quad (\text{B.36.2})$$

for all  $x \in F_\lambda$  and all  $y \in M$ . This follows easily from the definition of  $N(f)$ . In particular the restriction of  $f$  to  $F_\lambda$  is  $\lambda$ -Lipschitz.

A real-valued Lipschitz function on a subset of a metric space can always be extended to a Lipschitz function on the whole space, without increasing the norm. In this case we wish to use this fact to obtain a  $\lambda$ -Lipschitz function  $g_\lambda : M \rightarrow \mathbb{R}$  which equals  $f$  on  $F_\lambda$ . According to the usual recipe, we can obtain  $g_\lambda$  from the formula

$$g_\lambda(y) = \inf_{x \in F_\lambda} \{f(x) + \lambda d(x, y)\}, \quad y \in M. \quad (\text{B.36.3})$$

This function is  $\lambda$ -Lipschitz, as in Lemma 6.20, and it is easy to check that  $g_\lambda = f$  on  $F_\lambda$ .

How well does  $g_\lambda$  approximate  $f$  off of  $F_\lambda$ ? We have that

$$|g_\lambda(y) - f(y)| \leq 2\lambda \operatorname{dist}(y, F_\lambda) \quad \text{for all } y \in M. \quad (\text{B.36.4})$$

To see this let  $x$  be any element of  $F_\lambda$ . Then

$$|g_\lambda(y) - f(y)| \leq |g_\lambda(y) - g_\lambda(x)| + |f(y) - f(x)| \quad (\text{B.36.5})$$

since  $g_\lambda(x) = f(x)$ . Thus

$$|g_\lambda(y) - f(y)| \leq 2\lambda d(x, y), \quad (\text{B.36.6})$$

since  $g_\lambda$  is  $\lambda$ -Lipschitz and we have (36.2). Taking the infimum over  $x \in F_\lambda$  we get (36.4).

Thus  $g_\lambda$  provides a good approximation to  $f$  on all of  $M$ , with a very precise estimate. In practical situations on Euclidean spaces and some other spaces we have a good bound on the measure of  $M \setminus F_\lambda$ , and we can use this approximation to derive results about  $f$  from results about Lipschitz functions. Here is an example.

**B.36.7. Proposition:** *Suppose that  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is continuous. Then  $f$  is differentiable at almost every point for which  $N(f) < \infty$ .*

To prove this we let  $F_\lambda$  be defined as in (36.1). It suffices to show that  $f$  is differentiable at almost every point in  $F_\lambda$  for each  $\lambda > 0$ .

Let  $g_\lambda : \mathbb{R}^n \rightarrow \mathbb{R}$  be as above. Then  $g_\lambda$  is Lipschitz, and hence differentiable a.e.

Each  $F_\lambda$  is closed and therefore measurable, and this means that almost every element of  $F_\lambda$  is a point of density of  $F_\lambda$ . That is,

$$\lim_{r \rightarrow 0} \frac{|F_\lambda \cap B(x, r)|}{|B(x, r)|} = 1 \quad (\text{B.36.8})$$

for almost all  $x \in F_\lambda$ . This follows from Theorem 34.1, applied to the characteristic function of  $F_\lambda$ .

Suppose now that  $x \in F_\lambda$  is a point of density of  $F_\lambda$  and a point of differentiability of  $g$ . Let us show that  $f$  is also differentiable at  $x$ , and with the same gradient as  $g$ . It suffices to show that

$$\lim_{r \rightarrow 0} r^{-1} \sup_{y \in B(x, r)} |f(y) - g(y)| = 0. \quad (\text{B.36.9})$$

Because of (36.4) it suffices to show that

$$\lim_{r \rightarrow 0} r^{-1} \sup_{y \in B(x, r)} \text{dist}(y, F_\lambda) = 0. \quad (\text{B.36.10})$$

This last is an easy consequence of (36.8). (To see this it is easier to think about showing that the failure of (36.10) implies the failure of (36.8).)

Thus  $f$  is differentiable almost everywhere on each  $F_\lambda$ , and the proposition follows.

See [Stein]\$\_{SI}\$ for more information about pointwise differentiability results.

There are many variations and refinements of the techniques indicated in this section, using other types of maximal functions and more refined extension techniques.

### B.37. Maximal functions and snapshots.

Let us come back to the idea of snapshots of a function. Let  $f$  be a real-valued function in  $\mathbb{R}^n$ , and let us think about  $f$  in terms of Lipschitz or “almost-Lipschitz” properties. Each ball  $B$  in  $\mathbb{R}^n$  gives a snapshot of our function  $f$ , in the manner of (12.2). The Lipschitz condition means exactly that these snapshots are all bounded. The condition that  $N(f)(x) < \infty$  means that all of the snapshots of  $f$  on the balls  $B(x, r)$  are bounded. This implies that the snapshots of  $f$  on all balls containing  $x$  are then bounded, with a slightly worse constant.

Let  $\lambda > 0$  be given, and let  $F_\lambda$  be as in (36.1). Think of  $\mathbb{R}^n \times (0, \infty)$  as parameterizing the set of balls in  $\mathbb{R}^n$ , and hence the set of snapshots of  $f$ . Let  $\widehat{F}_\lambda$  denote the set of points in  $\mathbb{R}^n \times (0, \infty)$  which correspond to balls which contain an element of  $F_\lambda$ . On these balls we control the size of the snapshot of  $f$  in terms of  $\lambda$ .

One can picture  $\widehat{F}_\lambda$  as the union of the cones in  $\mathbb{R}^n \times (0, \infty)$  with aperture 1 and vertex in  $F_\lambda$ . If  $F_\lambda$  is large, then  $\widehat{F}_\lambda$  will be a large piece of  $\mathbb{R}^n \times (0, \infty)$ .

In the story of  $g_\lambda$  we are trying to build a function on  $\mathbb{R}^n$  whose snapshots associated to elements of  $\widehat{F}_\lambda$  look like the snapshots of  $f$  but whose behavior is good everywhere. This is an important point; we want to match the behavior of  $f$  at all scales, not just the values of  $f$  at individual points.

These principles make sense in greater generality. Maximal functions control the behavior of functions for all snapshots over balls containing a given point. When the maximal function is controlled on a set, the snapshots are controlled for a subset of  $\mathbb{R}^n \times (0, \infty)$  which is a union of cones. We can try to build a function which has approximately the same snapshots as the original function in the good region but which has better behavior in the bad region.

To understand this properly one should understand the Whitney extension theorem, Whitney cubes and their associated partitions of unity, as in [Stein]\$\_{SI}\$. They provide the tools for building the approximations that one needs on “the bad set” (e.g., the complement of  $F_\lambda$ ) with much more care and control. We shall not pursue this here.

We shall discuss however the “Calderón-Zygmund approximation” in Section 39, which provides a version of this idea corresponding to the size of functions rather than there smoothness. Before we do this we take up the preliminary topic of dyadic cubes.

### B.38. Dyadic cubes.

An interval  $I$  in the real line is said to be *dyadic* if it is of the form  $[j 2^k, (j + 1) 2^k]$ , where  $j$  and  $k$  are integers. The funny business with the

end points is made to ensure that the dyadic intervals of a fixed length provide a partition of  $\mathbb{R}$ . A cube  $Q$  in  $\mathbb{R}^n$  is said to be *dyadic* if it is a product of dyadic intervals of the same length. Thus  $\mathbb{R}^n$  is partitioned by the cubes of sidelength  $2^k$  for each integer  $k$ .

Dyadic cubes enjoy the following combinatorial property.

**B.38.1. Lemma:** *If  $Q$  and  $R$  are dyadic cubes in  $\mathbb{R}^n$ , then either  $Q \subseteq R$ ,  $R \subseteq Q$ , or  $Q \cap R = \emptyset$ .*

This is not very difficult to check. It is very useful because it permits us to avoid covering lemmas when working with dyadic cubes, using the following instead.

**B.38.2. Lemma:** *Given any collection  $\mathcal{C}$  of dyadic cubes in  $\mathbb{R}^n$ , the maximal elements of  $\mathcal{C}$  are pairwise disjoint.*

This is not to say that maximal elements always exist. They will under mild conditions, like a uniform bound on the size of the cubes in  $\mathcal{C}$ .

Lemma 38.2 is an easy consequence of Lemma 38.1. Let us give an application to illustrate how it can be used. Given a locally integrable function  $f$  on  $\mathbb{R}^n$ , define the *dyadic maximal function of  $f$*  by

$$f_\delta^*(x) = \sup_{Q \ni x} \frac{1}{|Q|} \int_Q |f(y)| dy, \quad (\text{B.38.3})$$

where the supremum is taken over all dyadic cubes that contain  $x$ .

This maximal function is bounded by a constant multiple of the maximal function given in (32.1), but the converse is not quite true. Thus we have the same estimates for  $f_\delta^*$  as for  $f^*$ , but let us take a closer look at (32.4) and give a more direct argument.

Assume that  $f \in L^1(\mathbb{R}^n)$ , let  $\lambda > 0$  be given, and set

$$E_\lambda = \{x \in \mathbb{R}^n : f_\delta^*(x) > \lambda\}, \quad (\text{B.38.4})$$

in analogy with (33.1). We can rewrite this as

$$E_\lambda = \bigcup_{Q \in \mathcal{C}} Q, \quad \text{where} \quad (\text{B.38.5})$$

$$\mathcal{C} = \left\{ Q \in \Delta : \frac{1}{|Q|} \int_Q |f(y)| dy > \lambda \right\}, \quad (\text{B.38.6})$$

and where  $\Delta$  denotes the collection of all dyadic cubes in  $\mathbb{R}^n$ . Let  $\mathcal{M}$  denote the collection of maximal elements of  $\mathcal{C}$ . We have that

$$E_\lambda = \bigcup_{Q \in \mathcal{M}} Q, \quad (\text{B.38.7})$$

because the definition of  $\mathcal{C}$  and the assumption that  $f \in L^1(\mathbb{R}^n)$  ensure that the elements of  $\mathcal{C}$  have bounded size, so that each element of  $\mathcal{C}$  is contained in a maximal element. Using Lemma 38.2 we obtain the disjointness of the elements of  $\mathcal{M}$ , and hence

$$\begin{aligned} |E_\lambda| &= \sum_{Q \in \mathcal{M}} |Q| \leq \lambda^{-1} \sum_{Q \in \mathcal{M}} \int_Q |f(y)| dy \\ &= \lambda^{-1} \int_{E_\lambda} |f(y)| dy \leq \lambda^{-1} \int_{\mathbb{R}^n} |f(y)| dy. \end{aligned} \quad (\text{B.38.8})$$

This gives us the analogue of (32.4) for the dyadic case.

In defining dyadic cubes we have used the special structure of Euclidean spaces, but in fact one can make similar constructions in much greater generality, as in [David]<sub>MG</sub>, [David]<sub>WSI</sub>, [Christ]<sub>SIO</sub>, and [Christ]<sub>CI</sub>. The constructions in [David]<sub>MG</sub> and [David]<sub>WSI</sub> are given for Ahlfors regular subsets of Euclidean spaces, but Assouad's embedding theorem (Theorem 20.1) permits them to be applied to general metric spaces.

A lot of analysis with respect to dyadic cubes can be formulated very abstractly through the idea of "martingales" in probability theory, but we shall not go into that here.

### B.39. The Calderón-Zygmund approximation.

Let  $f$  be an integrable function on  $\mathbb{R}^n$ , and let  $\lambda > 0$  be given. We would like to approximate  $f$  by a function which is never much larger than  $\lambda$ , and to do this in a way which respects the geometry of  $\mathbb{R}^n$ .

Let  $f_\delta^*$  denote the dyadic maximal function of  $f$ , as in (38.3). Let  $E_\lambda$  be as in (38.4), and set  $F_\lambda = \mathbb{R}^n \setminus E_\lambda$ . Let  $\mathcal{C}$  be as in (38.6), and let  $\mathcal{M}$  denote again the maximal elements of  $\mathcal{C}$ , so that (38.7) holds. Let us check that

$$\frac{1}{|Q|} \int_Q |f(y)| dy \leq 2^n \lambda \quad \text{when } Q \in \mathcal{M}. \quad (\text{B.39.1})$$

Let  $Q \in \mathcal{M}$  be given, and let  $T$  be the parent of  $Q$ , the (unique) dyadic cube in  $\mathbb{R}^n$  which contains  $Q$  and has sidelength twice that of  $Q$ . Then

$$\frac{1}{|T|} \int_T |f(y)| dy \leq \lambda \quad (\text{B.39.2})$$

because  $Q$  is a maximal element of  $\mathcal{C}$  and therefore  $T$  does not lie in  $\mathcal{C}$ . This implies (39.1), by an elementary calculation.

Define an approximation  $g$  to  $f$  by

$$\begin{aligned} g(x) &= f(x) \quad \text{when } x \in F_\lambda \\ &= \frac{1}{|Q|} \int_Q |f(y)| dy \quad \text{when } x \in Q, Q \in \mathcal{M}. \end{aligned} \quad (\text{B.39.3})$$

This is the Calderón-Zygmund approximation to  $f$  (for this choice of  $\lambda$ ).

We have that

$$|g(x)| \leq 2^n \lambda \quad \text{almost everywhere on } \mathbb{R}^n. \quad (\text{B.39.4})$$

This follows from (39.1) when  $x \notin F_\lambda$ . When  $x \in F_\lambda$  we use the fact that  $|f(x)| \leq f_\delta^*(x)$  almost everywhere. This last is easy to check for Lebesgue points, for instance.

Note that  $g = f$  except on  $E_\lambda$ , and that the measure of  $E_\lambda$  is controlled by (38.8). In fact we have that

$$\int_Q g(y) dy = \int_Q f(y) dy \quad (\text{B.39.5})$$

whenever  $Q$  is a dyadic cube which intersects  $F_\lambda$ . Actually (39.5) holds trivially for  $Q \in \mathcal{M}$ , which is not quite contained in the preceding assertion. We want to derive the general case from this one. Let  $Q$  be given, with  $Q \cap F_\lambda \neq \emptyset$ . Observe that  $Q \cap E_\lambda$  is the disjoint union of the elements of  $\mathcal{M}$  which are contained in  $Q$ . This is easy to check, as in Lemmas 38.1 and 38.2. This implies that

$$\int_{Q \cap E_\lambda} g(y) dy = \int_{Q \cap E_\lambda} f(y) dy, \quad (\text{B.39.6})$$

since we already know that (39.5) holds for the elements of  $\mathcal{M}$ . This yields (39.5) for  $Q$ , since  $f$  and  $g$  agree on the complement of  $E_\lambda$ .

We can think of (39.5) as saying that  $g$  approximates  $f$  well in terms of snapshots and not just point values, but snapshots in terms of dyadic cubes instead of balls.

We shall give applications of the Calderón-Zygmund approximation in the next two sections. See [Stein]<sub>SI</sub>, [Stein]<sub>HA</sub> for more information and other applications.

The constructions given here and in Section 36 are particularly close for the real line, where we can take a locally integrable function and integrate it to get a differentiable function. This case is captured better by the “rising sun lemma” (§5.5 on p.24 of [Stein]<sub>SI</sub>).

## B.40. The John-Nirenberg theorem.

Remember from Section 11 that the John-Nirenberg theorem provides higher integrability properties of  $BMO$  functions than are offered initially by the definition. In this section we sketch a proof of the theorem, which is based on the Calderón-Zygmund approximation.

Let us first put the  $BMO$  condition into a more convenient form. Let  $f$  be a locally integrable function on  $\mathbb{R}^n$ . Given a cube  $Q$  in  $\mathbb{R}^n$ , set

$$m_Q f = \frac{1}{|Q|} \int_Q f(y) dy, \quad (\text{B.40.1})$$

the average of  $f$  over  $Q$ . To say that  $f$  lies in  $BMO$  means that

$$\|f\|_{**} = \sup_Q \frac{1}{|Q|} \int_Q |f(y) - m_Q f| dy < \infty, \quad (\text{B.40.2})$$

where the supremum is taken over all cubes  $Q$ . It is not hard to check that this is equivalent to (11.1), and that the two seminorms are each bounded by constant multiples of the other.

We shall use the following formulation of the John-Nirenberg theorem. Suppose that  $\|f\|_{**} \leq 1$ . Then for any cube  $Q$  in  $\mathbb{R}^n$  and any integer  $j \geq 1$  we have that

$$|\{x \in Q : |f(x) - m_Q f| > j 2^{n+1}\}| \leq 2^{-j} |Q|. \quad (\text{B.40.3})$$

The point is to get exponential decay on the right hand side.

To prove this we apply the Calderón-Zygmund approximation from the preceding section. Let  $Q$  and  $j$  be given, and let us assume that  $Q$  is a dyadic cube. We can always reduce to that case by making a translation and dilation (which cause no trouble). Set

$$f_0(x) = (f(x) - m_Q f) \mathbf{1}_Q(x). \quad (\text{B.40.4})$$

Thus  $f_0 \in L^1(\mathbb{R}^n)$  and  $\int_{\mathbb{R}^n} |f_0(x)| dx \leq |Q|$ .

We apply the construction of the preceding section with  $f$  replaced by  $f_0$  and with  $\lambda = 2$ . If  $\mathcal{C}$  is as in (38.6), then  $Q$  is not an element of  $\mathcal{C}$ , and in fact all elements of  $\mathcal{C}$  are proper subcubes of  $Q$ . If  $E_\lambda = E_2$  and  $g$  are as before, then we have that

$$|E_2| \leq \frac{1}{2} |Q| \quad (\text{B.40.5})$$

$$|g| \leq 2^{n+1} \quad \text{a.e.} \quad (\text{B.40.6})$$

If  $j = 1$  then we get (40.3), because  $E_2$  contains the set in the left side of (40.3). What if  $j = 2$ ? In this case we repeat the argument on each cube  $T \in \mathcal{M}$ , where  $\mathcal{M}$  denotes the collection of maximal elements of  $\mathcal{C}$ . For each  $T \in \mathcal{M}$  define a new function  $f_T$  by

$$f_T(x) = (f(x) - m_T f) \mathbf{1}_T(x). \quad (\text{B.40.7})$$

For this function we have essentially the same information that we did for  $f_0$  on  $Q$ . We apply again the construction of the preceding section with  $f = f_T$  and  $\lambda = 2$  to obtain a set  $E_2(T)$  and an approximation  $g_T$  to  $f_T$  such that

$$|E_2(T)| \leq \frac{1}{2} |T| \quad (\text{B.40.8})$$

$$|g_T| \leq 2^{n+1} \quad \text{a.e.} \quad (\text{B.40.9})$$

By construction we have that  $f_T = g_T$  off of  $E_2(T)$ , and this implies that

$$|\{x \in T : |f(x) - m_T f| > 2^{n+1}\}| \leq \frac{1}{2} |T| \quad (\text{B.40.10})$$

for each  $T \in \mathcal{M}$ .

Notice that

$$|m_Q f - m_T f| \leq 2^{n+1} \quad \text{when } T \in \mathcal{M}. \quad (\text{B.40.11})$$

This is implicit in (40.6) with our definitions (and comes from (39.1)). Thus we obtain

$$|\{x \in T : |f(x) - m_Q f| > 2^{n+1} \cdot 2\}| \leq \frac{1}{2} |T| \quad (\text{B.40.12})$$

for each  $T \in \mathcal{M}$ , using (40.10). Now  $X_2 = \{x \in Q : |f(x) - m_Q f| > 2 \cdot 2^{n+1}\}$  is necessarily contained in  $E(2)$ , and hence in the union of the  $T$ 's, and we have that

$$|X_2| \leq \sum_{T \in \mathcal{M}} |X_2 \cap T| \leq \sum_{T \in \mathcal{M}} \frac{1}{2} |T|, \quad (\text{B.40.13})$$

by (40.12). Since the  $T$ 's are disjoint and their union is  $E(2)$  (as in (38.7)) we have that

$$|X_2| \leq \frac{1}{2} |E(2)| \leq \frac{1}{4} |Q|. \quad (\text{B.40.14})$$

This is exactly what we wanted. The point is that we won a second factor of  $1/2$ .

Now for each  $T$  we have a family of cubes  $\mathcal{M}(T)$  with the same properties as before, and in particular the average of  $|f_T|$  over any of the elements of  $\mathcal{M}(T)$  is bounded by  $2^{n+1}$ . This means that we can repeat the argument for each of them. Repeating the argument indefinitely gives (40.3) for each

$j$ , as desired. This completes our sketch of the proof of the John-Nirenberg theorem.

### B.41. Reverse Hölder inequalities.

We shall sketch now the proofs of some results discussed in Sections 17 and 18.

Let  $\omega$  be a positive locally integrable function on  $\mathbb{R}^n$ . We shall write

$$\omega(A) \quad \text{for} \quad \int_A \omega(x) dx \quad (\text{B.41.1})$$

when  $A$  is a measurable subset of  $\mathbb{R}^n$ , and we shall continue to write  $|A|$  for the Lebesgue measure of  $A$ . Let us assume that there exists an  $\epsilon > 0$  so that for each cube  $Q$  and each measurable subset  $E$  of  $Q$  we have that

$$\frac{|E|}{|Q|} \leq \epsilon \quad \text{implies} \quad \frac{\omega(E)}{\omega(Q)} \leq 1 - \epsilon. \quad (\text{B.41.2})$$

This is one of the forms of the  $A_\infty$  condition mentioned in Section 17, and in fact it is the weakest version. For the convenience of our proofs we shall be working with cubes instead of balls in this section though.

We would like to sketch here a proof of the fact that this assumption on  $\omega$  implies the existence of  $K, p > 1$  such that  $\omega \in L_{loc}^p$  and

$$\left( \frac{1}{|Q|} \int_Q \omega(x)^p dx \right)^{\frac{1}{p}} \leq K \frac{1}{|Q|} \int_Q \omega(x) dx \quad (\text{B.41.3})$$

for all cubes  $Q$  in  $\mathbb{R}^n$ . Here  $K$  and  $p$  depend only on  $\epsilon$  and  $n$ .

In order to prove (41.3) we shall show that there is a large constant  $L > 1$  so that if  $Q$  is any cube and

$$Z_j = \left\{ x \in Q : \omega(x) > L^j \frac{\omega(Q)}{|Q|} \right\}, \quad \text{then} \quad (\text{B.41.4})$$

$$\omega(Z_j) \leq (1 - \epsilon)^j \omega(Q), \quad (\text{B.41.5})$$

$j = 1, 2, 3, \dots$ . Actually we can take  $L = 2^n/\epsilon$ . It is not too difficult to show that this implies (41.3), and that (41.3) also implies (41.5) with a suitable choice of  $L$ .

To prove (41.5) we shall use an argument much like the one in the previous section for (40.3). Let a cube  $Q$  be given, which we may assume to be dyadic. Set

$$\lambda = 2^{-n} L \frac{\omega(Q)}{|Q|}, \quad (\text{B.41.6})$$

and let us apply the Calderón-Zygmund approximation (Section 39) to  $f(x) = \omega(x) \mathbf{1}_Q(x)$ . This gives a set  $E_\lambda$  and an approximation  $g$  of  $f$  with the usual properties. First

$$|E_\lambda| \leq \lambda^{-1} \int_{\mathbb{R}^n} f(x) dx = 2^n L^{-1} |Q|, \quad (\text{B.41.7})$$

because of (38.8). We also have that  $f = g$  on the complement of  $E_\lambda$ , so that

$$\omega(x) \leq 2^n \lambda = L \frac{\omega(Q)}{|Q|} \quad \text{on } Q \setminus E_\lambda. \quad (\text{B.41.8})$$

Let  $\mathcal{C}$  again be the collection of dyadic cubes defined by (38.6). These cubes must all be contained in  $Q$  in this case, because of our choices of  $\lambda$  and  $L$ . If  $\mathcal{M}$  denotes the collection of maximal elements of  $\mathcal{C}$ , then  $E_\lambda$  is the union of the cubes in  $\mathcal{M}$ , and for each cube  $R \in \mathcal{M}$  we have that

$$\frac{1}{|R|} \int_R f(y) dy \leq 2^n \lambda, \quad (\text{B.41.9})$$

as in (39.1). In the present case this converts to

$$\frac{\omega(R)}{|R|} \leq L \frac{\omega(Q)}{|Q|}. \quad (\text{B.41.10})$$

With  $L = 2^n/\epsilon$ , as above, (41.7) implies that

$$|E_\lambda| \leq \epsilon |Q|. \quad (\text{B.41.11})$$

Our assumption (41.2) implies now that

$$\omega(E_\lambda) \leq (1 - \epsilon) \omega(Q). \quad (\text{B.41.12})$$

This gives (41.5) when  $j = 1$ , because of (41.8).

What about  $j = 2$ , and larger values of  $j$ ? We can iterate the procedure, as in the previous section. We can take the cubes in  $\mathcal{M}$ , apply the Calderón-Zygmund approximation to each of them, and make the same computations as before, to obtain the analogue of (41.12) for each of those cubes, and then (41.5) with  $j = 2$  by a computation as in (40.13), (40.14). The Calderón-Zygmund approximations for the cubes in  $\mathcal{M}$  provides us with a new family of cubes, then we repeat the process for them to get (41.5) with  $j = 3$ , etc.

This completes our sketch of the proof of (41.5).

Let us explain how to use this fact for the results of Gehring described in Section 18. Specifically, we would like to show that if  $\omega$  is a positive

locally integrable function on  $\mathbb{R}^n$  for which there exist constants  $N > 0$  and  $0 < s < 1$  such that

$$\frac{1}{|Q|} \int_Q \omega(x) dx \leq N \left( \frac{1}{|Q|} \int_Q \omega(x)^s dx \right)^{\frac{1}{s}} \quad (\text{B.41.13})$$

for all cubes  $Q$ , then (41.3) holds for some choices of  $K, p > 1$ . (Compare with (18.6) and (18.7).) It suffices to show that (41.2) holds for some  $\epsilon > 0$  and all cubes  $Q$ .

Let  $\epsilon > 0$  be small, to be computed in a moment. Suppose to the contrary that there exists a cube  $Q$  and a measurable subset  $E$  of  $Q$  such that

$$\frac{|E|}{|Q|} \leq \epsilon \quad \text{and} \quad \frac{\omega(Q \setminus E)}{\omega(Q)} < \epsilon. \quad (\text{B.41.14})$$

We want to get a contradiction with (41.13) by showing that the right-hand side has to be too small. From Hölder's inequality we obtain that

$$\left( \frac{1}{|Q|} \int_{Q \setminus E} \omega(x)^s dx \right)^{\frac{1}{s}} \leq \frac{1}{|Q|} \int_{Q \setminus E} \omega(x) dx < \epsilon \frac{\omega(Q)}{|Q|}. \quad (\text{B.41.15})$$

For the other piece, we use Hölder's inequality to obtain

$$\begin{aligned} \left( \frac{1}{|Q|} \int_E \omega(x)^s dx \right)^{\frac{1}{s}} &\leq \left( \frac{1}{|Q|} \int_E \omega(x) dx \right) \cdot \left( \frac{1}{|Q|} \int_E dx \right)^{1-\frac{1}{s}} \\ &\leq \frac{\omega(Q)}{|Q|} \epsilon^{1-\frac{1}{s}}. \end{aligned} \quad (\text{B.41.16})$$

Combining this with (41.15) we get a contradiction to (41.13) if  $\epsilon$  is small enough, depending on  $N$  and  $s$ . Therefore (41.13) implies (41.2), and hence (41.3), as desired.

## B.42. Two useful lemmas.

In this section we record a couple of lemmas which capture information from maximal functions in convenient ways. These lemmas came up in Part III.

**B.42.1. Lemma:** *Suppose that  $f$  is a function in  $BMO$  on  $\mathbb{R}^n$  (or any space of homogeneous type for that matter). Given a ball  $B$  let  $m_B f$  denote the average of  $f$  over  $B$ . Let  $B_0$  be a fixed ball. Then there is a set  $E \subseteq B_0$  such that*

$$|B_0 \setminus E| \leq .01 |B| \quad \text{and} \quad (\text{B.42.2})$$

$$|m_{B_0} f - m_B f| \leq C(n) \|f\|_* \quad (\text{B.42.3})$$

whenever  $B$  is a ball which intersects  $E$  and  $\text{radius } B \leq \text{radius } B_0$ . Here  $\|f\|_*$  denotes the  $BMO$  norm of  $f$ , as in (11.1), and  $C(n)$  is independent of  $f$ ,  $B_0$ , and  $B$ .

That is, most of the averages of  $f$  over balls in a given ball  $B_0$  deviate from the average of  $f$  over  $B_0$  by a bounded amount. There is nothing special about .01 here, it was simply chosen for definiteness.

The proof of the lemma is quite easy. Given  $B_0$  define the auxiliary function  $f_0$  by

$$f_0(x) = (f(x) - m_{B_0} f) \mathbf{1}_{2B_0}(x). \quad (\text{B.42.4})$$

One can check that  $\frac{1}{|B_0|} \int_{B_0} |f_0(x)| dx$  is bounded by a constant multiple of the  $BMO$  norm of  $f$ . The lemma follows by applying the estimate (32.4) for the maximal function of  $f_0$  (with a suitable choice of  $\lambda$ ).

Of course Theorem 32.3 provides better estimates than the one that we stated, particularly if one combines it with the John-Nirenberg theorem.

There is a nice analogue of Lemma 42.1 for  $A_\infty$  weights.

**B.42.5. Lemma:** *Let  $\omega$  be an  $A_\infty$  weight on  $\mathbb{R}^n$ . Then there is a constant  $K$  such that for each ball  $B_0$  in  $\mathbb{R}^n$ , there is a set  $E \subseteq B_0$  such that (42.2) holds and*

$$K^{-1} m_{B_0} \omega \leq m_B \omega \leq K m_{B_0} \omega \quad (\text{B.42.6})$$

for all balls  $B$  which intersect  $E$  and have radius less than the radius of  $B_0$ . The constant  $K$  depends only on  $n$  and the  $A_\infty$  constant for  $\omega$ .

The fact that we can get the upper bound is an easy consequence of (32.4), applied to  $f(x) = \omega(x) \mathbf{1}_{2B_0}(x)$ , and with  $\lambda$  taken to be a large multiple of  $m_{B_0} \omega$ . The lower bound is more tricky. It can be derived from estimates for the maximal function of  $f(x) = \mathbf{1}_{2B_0}(x)$  taken with respect to  $\omega$  measure rather than Lebesgue measure. We can do this, because Section 32 applies to any space of homogeneous type,  $(\mathbb{R}^n, |x - y|, \omega(x) dx)$  in particular. We conclude that the lower bound in (42.6) is true for all balls  $B$  which touch a set  $E' \subseteq B_0$ , where  $B_0 \setminus E'$  has small measure with respect to  $\omega$ . The  $A_\infty$  property permits us to obtain that  $B_0 \setminus E'$  has small Lebesgue measure, although for this assertion we are using more of the theory about  $A_\infty$  weights.

Alternatively one can derive Lemma 42.5 from the fact that the logarithm of an  $A_\infty$  weight lies in  $BMO$ , which permits a reduction to Lemma 42.1.

In any case we shall not give the details. They are not difficult given the theory that exists, but in the present context it is better to just give a flavor and move on.

### B.43. Better methods for small oscillations.

There were two main ideas in the preceding sections, maximal functions and Calderón-Zygmund approximations. They provide very powerful tools for managing good behavior that occurs only some of the time.

A basic deficiency of these methods is that they are not as efficient at detecting small oscillations as they are at controlling large oscillations. Indeed, consider the following question. Suppose that  $f$  is an  $L^1$  function on  $\mathbb{R}^n$ , so that

$$\lim_{r \rightarrow 0} \frac{1}{|B(x, r)|} \int_{B(x, r)} f(y) dy = f(x) \quad (\text{B.43.1})$$

for almost all points  $x \in \mathbb{R}^n$ . What can we say about this limiting process? The limit exists, but can we get an estimate? We cannot get any kind of uniform control on the rate of convergence, but can we say something about the number of oscillations? For instance, let  $\epsilon > 0$  be given, pick a point  $x$ , start at  $r = 1$ , and steadily shrink  $r$  to 0. As  $r$  is shrinking, ask how many times the quantity

$$\frac{1}{|B(x, r)|} \int_{B(x, r)} f(y) dy \quad (\text{B.43.2})$$

oscillates by at least  $\epsilon$ . The answer is finite for almost all points, because of the existence of the limit, but can we get an estimate? One can ask analogous questions for the differentiability of Lipschitz functions.

The method of maximal functions does not deal with this question so well. The matter of small oscillations there is hidden in the approximation of  $L^1$  functions by continuous functions, which does not come with quantitative estimates. (Maximal functions and Calderón-Zygmund approximations do however cooperate well with objects that are more sensitive to oscillations, such as singular integral operators, even if they are not so useful in detecting small oscillations directly. See [Stein]<sub>SI</sub>, [Stein]<sub>HA</sub>.)

Carleson's solution of the Corona problem provides a way to deal with this kind of question. Garnett's book [Garn] is the basic reference for this topic. See also Chapter 2 of Part IV of [Dav-Sem]<sub>UR</sub>, which is aimed more at Lipschitz functions and geometry. Carleson's method is not very difficult to understand, but we do not have room for it here. Still it would be nice to give a flavor of it. Suppose that  $f \in L^2(\mathbb{R}^n)$ . Given any integer  $k$  let  $f_k$  be defined as follows: for each dyadic cube  $Q$  in  $\mathbb{R}^n$  of sidelength  $2^k$  we set

$$f_k(x) = \frac{1}{|Q|} \int_Q f(y) dy \quad \text{when } x \in Q. \quad (\text{B.43.3})$$

We have that  $f_k \rightarrow f$  in  $L^2$  as  $k \rightarrow -\infty$  and  $f_k \rightarrow 0$  in  $L^2$  as  $k \rightarrow \infty$ . Thus we can write  $f$  as a telescoping series

$$f = \sum_{k=-\infty}^{\infty} (f_k - f_{k+1}). \quad (\text{B.43.4})$$

(Compare with (6.31).) In fact the functions  $f_k - f_{k+1}$  are orthogonal to each other. This is easy to check, using the observations that  $f_k - f_{k+1}$  is constant on dyadic cubes of size  $2^k$  and has integral zero over dyadic cubes of larger size. Orthogonality implies that

$$\|f\|_2^2 = \sum_{k=-\infty}^{\infty} \|f_k - f_{k+1}\|_2^2. \quad (\text{B.43.5})$$

(Compare with Theorem 6.3 and (12.5).) One can compute from this that differences between averages of  $f$  over successive dyadic cubes are often small. The bound is not so strong that it implies immediately the existence of  $\lim_{k \rightarrow -\infty} f_k(x)$  almost everywhere, but it provides quantitative bounds not given by the existence of the pointwise limits.

In (43.4) we decompose  $f$  according to the obvious layering of dyadic cubes according to size. In fact any decomposition leads to orthogonality. In Carleson's Corona construction one chooses a decomposition adapted to the oscillations of the given function through a stopping-time argument.

The question of measuring oscillations arose before in Section 29, where we sought quantitative bounds on the extent to which a Lipschitz function is approximated by affine functions. In that case too there were  $L^2$  estimates at the heart of the matter (as in (29.20)). Once one can account for oscillations in a meaningful way, as in Theorem 29.10, one can try to make geometrical arguments using real-variable methods. Jones' proof of Theorem 28.2 provides a nice example of this. It works roughly as follows. We start with a Lipschitz mapping on the unit cube  $Q$  in  $\mathbb{R}^n$ . Given a dyadic subcube  $T$  of  $Q$ , consider the question of whether

$$\frac{|f(T)|}{|T|} \quad (\text{B.43.6})$$

is small or not, where "small" means less than some threshold that has to be computed in the proof. Let  $E$  denote the union of the cubes for which this ratio is small. Then  $E$  is the disjoint union of the maximal cubes with this property, and one can show that the image of  $E$  is small under  $f$ . This basically means that it can be ignored.

Now look at the dyadic cubes  $T$  with the property that  $f$  is very well approximated by an affine function on the double of  $T$ , say. The degree of

approximation should be normalized properly, as in (29.1), and then one has a good approximation for most cubes, in the sense of Carleson sets. The conclusion is that for most points  $x \in Q$ , the number of cubes  $T$  containing  $x$  which are bad for approximating  $f$  by an affine function is uniformly bounded, except for a set of  $x$ 's of small measure. Again we can ignore the bad set because of the formulation of Theorem 28.2.

If you have a cube  $T$  on which  $f$  is sufficiently well approximated by an affine function, and for which (43.6) is not too small, then  $f$  itself must be approximately bi-Lipschitz on that cube. The reason is that the affine function that makes the approximation will have to be bi-Lipschitz with a reasonable bound, because otherwise (43.6) would have to be small. (Compare with Sard's theorem.)

If  $x$  is a point that has not been excluded so far, then all but a bounded number of the dyadic cubes  $T$  containing  $x$  will have the good property just mentioned, of approximate bi-Lipschitzness. To complete the proof of Theorem 28.2 one makes a coding argument to sort these points into a bounded number of sets on which  $f$  is bi-Lipschitz.

See [Dav–Sem]<sub>QR</sub> for variations on this theme.

Notice that these arguments of Carleson and Jones treat the geometry of snapshots differently from the method of maximal functions and Calderón-Zygmund approximations.

#### B.44. Real-variable methods and geometry.

We have discussed real-variable methods mostly in terms of analysis of functions, but they can be employed in geometric problems too. We have already seen some examples of this, in studying the behavior of Lipschitz or quasisymmetric mappings, or in cases where the geometry of a space is governed by a function (like the unit normal vectors on an almost-flat hypersurface, or metric doubling measures). One can also try to work directly with the geometry of sets and spaces. The idea of Calderón-Zygmund approximations can be useful in studying the geometry of sets. This occurs in [David]<sub>PC</sub>, [David]<sub>SR</sub>, [David]<sub>WSI</sub>, for example. Maximal functions have not been as effective as in the context of functions. They are useful in matters of mass distribution, but in questions of smoothness one has the problem that the regularity of a function is reflected in the size of its derivative while the size of a tangent plane has less meaning (unless there is a question of mass distribution). In geometry it often seems better to study measurements of oscillation than of size. One can measure the extent to which a set can be approximated in a ball by a plane or some other standard model, as in [Jones]<sub>Squ</sub>, [Jones]<sub>Rec</sub>, [Dav–Sem]<sub>SI</sub>, [Dav–Sem]<sub>UR</sub>,

$[\text{Sem}]_{\text{Rect}}$ .

For the purposes of geometry, my favorite real-variable methods come from Carleson's corona construction. It is sensitive to small oscillations while not depending so much on linear structure as other methods from analysis. Its basic language of Carleson sets and stopping-time regions provides good tools for organizing information, for separating "good parts" from "bad parts", and for measuring the amount of bad behavior and the size of the transition region. This basic language is often a good place to start in a problem, an initial framework with broad applicability and a penchant for clearing away the dust so that one can see the main issues more clearly.

At first the corona construction was applied to functions that govern the geometry of a set, such as Riemann mappings and unit normal vectors, as in [GaJ], [Jones]<sub>S<sub>qu</sub></sub>, [Jones]<sub>Rec</sub>, [Sem]<sub>Rect</sub>. In [Dav–Sem]<sub>S<sub>I</sub></sub> and [Dav–Sem]<sub>U<sub>R</sub></sub> it is applied more directly to sets themselves. See Chapter 3 of Part I of [Dav–Sem]<sub>U<sub>R</sub></sub> for the general language of the corona method.

The methods from the corona construction are very general but do not normally finish a problem on their own. The strongest real-variable method for actually resolving a problem in geometry that I know is that of David [David]<sub>MG</sub>. It addresses the question of when a Lipschitz mapping between two spaces admits a large bi-Lipschitz piece, which can provide a way to parameterize part of the domain. It proceeds by analyzing the possible configuration of snapshots, reducing the matter to one scenario that can cause trouble but which can sometimes be prevented by natural assumptions. The method is purely geometric, in that it can function without starting with some information from linear analysis. The principles are quite simple even if the details are more complicated. See also [David]<sub>WS<sub>I</sub></sub>, [Dav–Sem]<sub>U<sub>R</sub></sub>.

One should keep in mind that these real-variable methods are best suited to finding good behavior most of the time, granting the existence of singularities. For some purposes this is a high price to pay, in topology, for instance. Real variable methods provide a certain kind of language with which to address geometric complexity. They are very good for what they do, but they can only do certain things.

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## Appendix C

# Paul Levy's Isoperimetric Inequality

by M. Gromov

Consider the standard  $(n + 1)$ -dimensional sphere  $S^{n+1}$  and a domain  $V_0 \subset S^{n+1}$  with smooth boundary. The classical isoperimetric inequality provides the following lower bound for the  $n$ -dimensional volume  $\text{vol}(\partial V_0)$  of the boundary  $\partial V_0$ .

Denote by  $\alpha$  the ratio  $\text{vol}(V_0) / \text{vol}(S^{n+1})$ , where “vol” means the  $(n+1)$ -dimensional volume, and take a ball  $B_\alpha \subset S^{n+1}$  with  $\text{vol}(B_\alpha) = \alpha \text{vol}(S^{n+1})$ . Denote by  $s(\alpha)$  the  $n$ -dimensional volume of the boundary sphere  $\partial B_\alpha$  and denote by  $\text{Is}_{n+1}(\alpha)$  the ratio  $s(\alpha) / \text{vol}(S^{n+1})$ .

### Classical Isoperimetric Inequality.

$$\frac{\text{vol}(\partial V_0)}{\text{vol}(S^{n+1})} \geq \text{Is}_{n+1}(\alpha), \quad \alpha = \frac{\text{vol}(V_0)}{\text{vol } S^{n+1}}.$$

Observe that by applying this inequality to domains with diameters converging to zero, we come to the isoperimetric inequality in the Euclidean space  $\mathbb{R}^{n+1}$ .

Back in 1919, Paul Levy extended the classical isoperimetric inequality to the convex hypersurfaces in  $\mathbb{R}^{n+2}$ , and he found a striking infinite dimensional application of his result. (See Chapter IV of the third part of his book [Levy]).

We show in this note that Levy's method works for all Riemannian manifolds. As an application, we obtain some estimates for the eigenvalues

of the Laplacian on a Riemannian manifold.

**1. Isoperimetric inequality.** For a compact Riemannian manifold  $V$ , we denote by  $\text{vol}(V)$  its total volume and by Ricci the Ricci tensor. We set

$$R(V) = \inf_{\tau} \text{Ricci}(\tau, \tau),$$

where  $\tau$  runs over all unit tangent vectors of  $V$ .

*Let  $V$  be a closed  $(n + 1)$ -dimensional manifold and let  $V_0 \subset V$  be a domain with smooth boundary. If  $R(V) \geq n = R(S^{n+1})$ , then*

$$\frac{\text{vol}(\partial V_0)}{\text{vol}(V)} \geq \text{Is}_{n+1}(\alpha) \geq \text{Is}_{n+1}(\alpha), \quad \alpha = \frac{\text{vol}(V_0)}{\text{vol}(V)}, \quad (*)$$

where  $\text{Is}_{n+1}(\alpha)$  is the same function as in the classical isoperimetric inequality.

**Remarks and corollaries.** When  $V = S^{n+1}$ , the inequality  $(*)$  becomes the classical isoperimetric inequality.

Our proof (see §4) shows that equality in  $(*)$  holds only for the standard pair  $(V, V_0) = (S^{n+1}, B_\alpha)$ .

If one applies  $(*)$  to the  $\varepsilon$ -neighborhoods  $U_\varepsilon$  of  $V_0$  and integrates over  $\varepsilon$ , one gets

$$\frac{\text{vol}(U_\varepsilon)}{\text{vol}(V_0)} \geq \frac{\text{vol}(A_\varepsilon)}{\text{vol}(B_\alpha)},$$

where  $A_\varepsilon$  denotes the  $\varepsilon$ -neighborhood of  $B_\alpha$  in  $S^{n+1}$ .

**2. The first eigenvalue.** Denote by  $\lambda_1$  the first eigenvalue of the Laplacian on  $V$  and by  $D$  the diameter of  $V$ .

*If  $R(V) \geq -n$ ,  $0 < n = \dim(V) - 1$ , then*

$$\lambda_1 \geq \exp(-2nD). \quad (**)$$

This inequality (in a sharper form) follows from the inequality  $(\text{Is}'')$  of §4 and the following theorem of Cheeger (see [Che]RBLD):

$$\lambda_1 \geq \frac{1}{4} \left( \inf_{V_0} \frac{\text{vol}(\partial V_0)}{\text{vol}(V_0)} \right)^2,$$

where  $V_0$  runs over all domains in  $V$  with smooth boundary such that  $\text{vol}(V_0)/\text{vol}(V) \leq 1/2$ . Some other relations of this type can be found in [Maz] and [Bur–Maz].

The inequality  $(**)$  was conjectured by Cheeger, and it was proved in some cases by Yau [Yau]<sub>JCFE</sub> and Li [Li], see also [Yau]<sub>FTPCRM</sub>.

I was recently informed that Yau found an independent proof<sup>1</sup> of  $(**)$ .

We refer to [Ber–Gau–Maz] and [Osser] for further information on the spectrum of the Laplacian. In §5 we generalize this inequality to all eigenvalues  $\lambda_i$ .

**3. Levy–Heintze–Karcher comparison theorem.** Let  $H \subset V$  be a smooth hypersurface with a normal unit vector field  $\nu$ . Denote by  $\exp : H \times \mathbb{R}_+ \rightarrow V$  the normal exponential map in the direction  $\nu$  and denote by  $J = J(h, t)$ ,  $h \in H$ ,  $t \in \mathbb{R}_+$ , the Jacobian of this map.

Consider also a model pair  $(\bar{V}, \bar{H})$ , where  $\bar{V}$  has constant sectional curvature  $\delta$ , and  $\bar{H}$  is a totally umbilic hypersurface of mean curvature  $\eta$  (relative to the preferred direction  $\bar{\nu}$ ). Denote by  $\bar{J}(t) = \bar{J}_{\eta\delta}(t)$  the Jacobian of the corresponding exponential map.

Take a point  $h \in H$  such that at this point the mean curvature of  $H$  (in the direction  $\nu$ ) is not less than  $\eta$ . Take a point  $t \in \mathbb{R}_+$  such that the segment  $h \times [0, t]$  is sent by the exponential map to a distance minimizing geodesic segment, i.e.,  $\text{dist}(H, \exp(h, t)) = t$ .

If  $R(V) \geq n\delta = R(\bar{V})$ ,  $n = \dim H = \dim \bar{H}$ , then  $|J(h, t)| \leq \bar{J}(t)$ .

The proof can be found in [Heint–Kar]. See also [Buy] for some related results.

The explicit formula for  $\bar{J}(t)$  is as follows. Set  $s_\delta(t) = \delta^{-1/2} \sin(\delta^{-1/2}t)$  for  $\delta > 0$ ,  $s_0(\delta) = t$ , and  $s_\delta(t) = |\delta|^{-1/2} \sinh(|\delta|^{-1/2}t)$  when  $\delta < 0$ . Using these notations, we have (see [Heint–Kar])

$$\bar{J}_{\eta\delta}(t) = \left( \frac{ds_\delta(t)}{dt} - ns_\delta(t) \right)^n.$$

It is convenient to use another function  $\bar{J}^+(t)$  defined as follows:  $\bar{J}^+(t) = \bar{J}(t)$  when  $t$  is less than the first zero  $t_0$  of  $\bar{J}(t)$  and  $\bar{J}^+(t) = 0$  for  $t \geq t_0$ .

**Corollary: (See [Heint–Kar]).** Let a domain  $V_0 \subset V$  be bounded by a smooth hypersurface  $H = \partial V_0$  whose mean curvature is everywhere not less than  $\eta$  (relative to the inward normal). Then

$$\text{vol}(V_0) \leq \text{vol}(\partial V_0) \int_0^d \bar{J}^+(t) dt,$$

where  $d = \sup_{v \in V_0} \text{dist}(v, \partial V_0)$ . (Observe that  $d \leq D = \text{diam}(V)$ .)

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<sup>1</sup>See [Li–Yau], where the treatment is, in many respects, more complete and precise than ours.

**4. Main inequalities.** Let  $V$  be a closed  $(n+1)$ -dimensional manifold with  $R(V) = n\delta$ ,  $-\infty < \delta < \infty$ , and let  $H \subset V$  be an arbitrary smooth hypersurface which divides  $V$  into two domains  $V_0$  and  $V_1$  with common boundary  $H$ .

*There exist positive numbers  $d_0$  and  $d_1$  with  $d_0 + d_1 \leq D = \text{diam } V$  and an  $\eta \in (-\infty, \infty)$  such that*

$$\text{vol}(V_0) \leq \text{vol}(H) \int_0^{d_0} \overline{J}_{\eta\delta}^+(t) dt, \quad (\text{Is})$$

$$\text{vol}(V_1) \leq \text{vol}(H) \int_0^{d_1} \overline{J}_{\eta\delta}^+(t) dt.$$

**Corollaries:** Observe that for  $\eta \geq 0$  we have  $\overline{J}_{\eta\delta}^+(t) \leq \overline{J}_{0\delta}^+(t)$ , and in view of the explicit formula for  $\overline{J}$ , the inequality (Is) implies:

If  $\text{vol}(V_0) \leq \text{vol}(V_1)$ , then

$$\text{vol}(V_0) < \text{vol}(\partial V_0) \int_0^D \left( \cosh(|\delta|^{-1/2} t) \right)^n dt. \quad (\text{Is}')$$

Notice that this inequality is interesting only when  $R(V) \leq 0$ . The following inequality is most interesting when  $R(V) > 0$ .

Set  $\alpha = \text{vol}(V_0)/\text{vol}(V)$ ,  $\beta = 1 - \alpha$ , and denote

$$\mu(\eta) = \min \left( \alpha^{-1} \int_0^D \overline{J}_{\eta\delta}^+(t) dt, \beta^{-1} \int_0^D \overline{J}_{-\eta\delta}^+(t) dt \right).$$

By combining the inequalities (Is), we immediately get

$$\frac{\text{vol}(H)}{\text{vol}(V)} \geq \inf_{-\infty < \eta < \infty} (\mu(\eta))^{-1}. \quad (\text{Is}'')$$

When  $\delta = 1$  and  $D = \infty$ , a straightforward calculation shows that

$$\inf_{-\infty < \eta < \infty} (\mu(\eta))^{-1} = \text{Is}_{n+1}(\alpha) = \text{Is}_{n+1}(\beta),$$

and hence, (Is'') implies the inequality (\*) from §1.

**Proof of (Is).** Fix an  $\alpha$ ,  $0 < \alpha < 1$ , and consider all hypersurfaces in  $V$  which divide  $V$  into two parts  $V_0, V_1$  with  $\text{vol}(V_0) = \alpha$ ,  $\text{vol } V_1 = 1 - \alpha$ . Among these hypersurfaces, there is one with minimal  $n$ -dimensional volume (see [Alm]Exi). Suppose for a minute that this minimal hypersurfaces

is nonsingular. In such a case, it has *constant* mean curvature. We denote by  $\eta$  the value of this curvature relative to the normal looking into  $V_0$ . The curvature in the direction looking into  $V_1$  is  $\eta$ , and applying the Corollary of §3 to  $V_0$  and  $V_1$ , we get (Is).

**About the singularity.** When  $\dim V \leq 7$ , the minimal hypersurface  $H$  dividing  $V$  in the given volume proportion is known to be nonsingular (see [Alm]Exi), and the proof of (Is) is complete. In the general case,  $H$  may have a singular locus, but it does not affect our proof due to the following

**Lemma:** *Take a point  $v \in V$  and a geodesic segment  $\gamma \in V$  having  $v$  as one endpoint and  $h \in H$  as the other, such that  $\text{length}(\gamma) = \text{dist}(v, H)$ . Then the point  $h \in H$  is nonsingular.*

**Proof.** Take the sphere (relative to the Riemannian metric in  $V$ ) centered at the center of  $\gamma$  and having radius  $\text{dist}(v, H)/2$ . This sphere meets  $H$  only at  $h$ , and it is smooth near this point. It follows that the tangent cone to  $H$  at  $h$  is contained in a half-space and hence (see [Alm]Exi), the point  $h$  is nonsingular.

**Estimates for  $\lambda_i$ ,  $i > 1$ .** Our method of estimating  $\lambda_1$  can be extended to other eigenvalues of the Laplacian on  $V$ , but we shall establish these estimates by a more elementary method because for the higher  $\lambda_i$ , the more refined Levy's method does not give much better constants.

**Notations.** Let  $V$  be a compact Riemannian manifold of dimension  $n+1 \geq 2$ . Denote by  $N(\varepsilon)$ ,  $\varepsilon > 0$ , the minimal number  $N$  such that  $V$  can be covered by  $N$  balls of radius  $\varepsilon$ . Notice that

$$N(\varepsilon) \geq \frac{D}{2}$$

$$N(D) = 1, \quad D = \text{diam}(V).$$

Denote by  $b_{n+1}(\varepsilon)$  the volume of the  $\varepsilon$ -ball in the  $(n+1)$  dimensional hyperbolic space of curvature  $-1$ . The Rauch comparison theorem (see [Che–Ebin]) implies that for a closed  $V$  with  $R(V) \geq -n$ , one has

$$N(\varepsilon) \geq (b_{n+1}(\varepsilon))^{-1} \text{vol}(V).$$

On the other hand, we shall see below that

$$N(\varepsilon) \leq b_{n+1}(D)(b_{n+1}(\varepsilon/2))^{-1},$$

and, more generally, for  $\varepsilon_1 \geq \varepsilon$ , one has

$$N(\varepsilon_1) \leq N(\varepsilon) \leq b_{n+1}(2\varepsilon_1 + \varepsilon/2)(b_{n+1}(\varepsilon/2))^{-1} N(\varepsilon_1).$$

**Theorem:** *There are two positive constants  $C_1$  and  $C_2$  depending on  $n$ , such that for any closed Riemannian manifold  $V$  of dimension  $n+1 \geq 2$  with  $R(V) \geq -n$ , and for each positive  $\varepsilon \leq D = \text{diam}(V)$ , one has the following estimates for the eigenvalue  $\lambda_i$  with  $i = N(\varepsilon)$*

$$\varepsilon^{-2} C_1^{1+\varepsilon} \geq \lambda_i \geq \varepsilon^{-2} C_2^{1+\varepsilon}.$$

**Corollary:** Applying these inequalities to  $\varepsilon = 1$  and using the estimates for  $N(\varepsilon)$  above, we get

- (a) if  $i \leq D/2$ , then  $\lambda_i \leq \text{const}_n = C_1^2$ ,
- (a') if  $i \leq \text{vol}(V)/b_{n+1}(1)$ , then  $\lambda_i \leq \text{const}_n = C_1^2$ ,
- (b) if  $i \geq b_{n+1}(D)(b_{n+1}(1/2))^{-1}$ , then  $\lambda_i \geq \text{const}_n = C_2^2$ .

**Remark:** The inequality  $\lambda_i \leq \varepsilon^{-2} C_1^{1+\varepsilon}$  and its corollaries (a) and (a') are not new. A more precise result is due to Cheng (see [Cheng]), but we give the proof here for the sake of completeness.

**Proof.** We start with several simple lemmas.

**(A) (Rauch Theorem):** *Take a point  $v \in V$  and two balls  $B, B_1$  centered at  $v$  of radii  $r$  and  $r_1 > r$ . Let  $A \subset B_1$  be a star-convex set, i.e., a Borel set such that for each point  $a \in A$ , each geodesic segment which joins  $v$  with  $a$  and has length =  $\text{dist}(v, a)$  is contained in  $A$ . If  $\text{Ricci}(V) \geq -n$ , then*

$$\frac{\text{vol}(A \cap B_1)}{\text{vol}(A \cap B)} \leq \frac{b_{n+1}(r_1)}{b_{n+1}(r)},$$

where “vol” denotes the  $(n+1)$ -dimensional measure in  $V$ . In particular, one has

$$\frac{\text{vol}(B_1)}{\text{vol}(B)} \leq \frac{b_{n+1}(r_1)}{b_{n+1}(r)}.$$

When  $B' \subset V$  is a radius- $r$  ball centered at  $v' \in V$  with  $\text{dist}(v, v') = d$ , we get

$$\frac{\text{vol}(B_1)}{\text{vol}(B')} \leq \frac{b_{n+1}(r_1 + d)}{b_{n+1}(r)}.$$

It follows that each  $\varepsilon_1$ -ball in  $V$  can be covered by

$$p \leq b_{n+1}(2\varepsilon_1 + \varepsilon/2)(b_{n+1}(\varepsilon/2))^{-1}$$

balls of radius  $\varepsilon$ . It implies the relation between  $N(\varepsilon)$  and  $N(\varepsilon_1)$  which was stated above.

(A') Denote by  $a_n(\varepsilon)$  the  $n$ -dimensional volume of the  $\varepsilon$ -sphere in the  $(n+1)$ -dimensional hyperbolic space of curvature  $-1$ . The  $n$  dimensional volume of the set  $\Lambda \cap \partial B$  and the  $(n+1)$ -dimensional volume of the part  $A'$  of  $A$  contained in the complement  $B_1 \setminus B$  (i.e.,  $A' = A \cap (B_1 \setminus B)$ ) are related as follows:

$$\frac{\text{vol}(A')}{\text{vol}(A \cap \partial B)} \leq \frac{b_{n+1}(r_1) - b_{n+1}(r)}{a_n(r)}.$$

**Proof.** Both theorems (A) and (A') follow from the local Rauch theorem (see [Che–Ebin]). Observe that they can also be easily reduced to the Levy–Heintze–Karcher comparison theorem.

(B) Let  $(V, v)$  be as above and consider an arbitrary Borel set  $W \subset V$ . Let  $H \subset V$  be a smooth hypersurface (possibly with a boundary) such that for each  $w \in W$ , each distance-minimizing geodesic segment  $\gamma$  between  $w$  and  $v$  (“distance-minimizing” means  $\text{length}(\gamma) = \text{dist}(v, w)$ ) meets  $H$  at a point  $h \in H \cap \gamma$ . Let  $d_1 = d_1(\gamma)$  denote the distance  $\text{dist}(v, h)$  and  $d_2 = \text{dist}(h, w) = \text{length}(\gamma) - d_1$ . (When  $\gamma$  meets  $H$  at several points, we take for  $h$  the nearest point to  $w$ .) The  $(n+1)$ -dimensional volume of  $W$  and the  $n$  dimensional volume of  $H$  are related by the inequality

$$\frac{\text{vol}(W)}{\text{vol}(H)} \leq \sup_{\gamma} \frac{b_{n+1}(d_1(\gamma) + d_2(\gamma)) - b_{n+1}(d_1(\gamma))}{a_n(d_1(\gamma))}.$$

**Proof.** This immediately follows from (A'). Observe that (A') implies a more precise inequality. Denote by  $H' \subset H$  the set of all intersection points  $\gamma \cap H$  and for an  $h \in H'$  denoted by  $\alpha(h)$  the angle between  $H$  and the corresponding  $\gamma$ . Set  $d_1(h) = \text{dist}(h, v)$ ,  $d_2(h) = \text{dist}(h, w)$ . Now one has

$$\text{vol}(W) \leq \int_{H'} \left( \frac{b_{n+1}(d_1(h) + d_2(h)) - b_{n+1}(d_1(h))}{a_n(d_1(h))} \right) \sin(\alpha(h)) d\mu,$$

where  $d\mu$  denotes the  $n$ -dimensional measure in  $H'$  induced from  $H$ .

(C) Let  $V$  be an arbitrary closed Riemannian manifold and let  $H$  be a closed hypersurface dividing  $V$  into two parts  $V_0$  and  $V_1$ . Let  $W_0 \subset V_0$ ,  $W_1 \subset V_1$  be two Borel sets of positive measure. Then there is a point  $w_0$  in one of the sets  $W_0$ ,  $W_1$ , say in  $W_0$ , and a subset  $W$  in another set, say in  $W_1$ , such that each distance minimizing segment joining  $w_0$  with an arbitrary point  $w_1 \in W$  meets  $H$  at a point  $h$  with  $\text{dist}(w_0, h) \geq \text{dist}(w_1, h)$ , and such that

$$\text{vol}(W) \geq \frac{1}{2} \text{vol}(W_1).$$

**Proof.** Consider the product  $W_0 \times W_1 \subset V \times V$  and the set  $X \subset W_0 \times W_1$  of the points  $(w_0, w_1)$  which can be joined (in  $V$ ) by the only one shortest segment  $\gamma$ . This set has full measure in  $W_0 \times W_1$ . Denote by  $Y \subset X$  the set of pairs  $(w_0, w_1)$  such that for an intersection point  $h$  of  $H$  with the corresponding  $\gamma$ , we have  $\text{dist}(w_0, h) \geq \text{dist}(w_1, h)$ . Denote by  $X' \subset W_1 \times W_0$  the set corresponding to  $X$  under the natural involution in  $V \times V$ . Denote by  $\tilde{Y} \subset X'$  the set of pairs  $(w_1, w_0)$  such that for the corresponding  $h$  we have  $\text{dist}(w_1, h) \geq \text{dist}(w_0, h)$ . One of the sets  $Y, \tilde{Y}$  must contain at least one half of the total measure of  $X$  (or of  $X'$ ), and we can assume that this is the case with  $Y$ . By the Fubini theorem, there exists a point  $w_0 \in W_0$  such that the intersection  $w_0 \times W_1 \cap Y$  contains at least one half of the total measure of  $W_1$ .

We are now ready to prove a version of the inequality (Is') of §4. We apply (C) to the manifolds  $V_0, V_1$  themselves, and we find a point  $w_0 \in V_0$  and a set  $W \subset V_1$  as in (C). By using (B), we get

$$\text{vol}(V_1) \leq 2 \text{vol}(W) \leq 2 \text{vol}(H) \frac{b_{n+1}(D) - b_{n+1}(D/2)}{a_n(D/2)}.$$

Of course, if  $W$  happens to be in  $V_0$ , we get such estimates for  $\text{vol}(V_0)$ , but, in any case, we have an estimate for the smaller of the manifolds  $V_0$  and  $V_1$ . According to the Cheeger theorem (see §2), this is sufficient for an estimate of  $\lambda_1$  from below. In order to get an estimate for the rest of the  $\lambda_i$ , we need one more lemma.

(D) Let  $V$  be an arbitrary compact Riemannian manifold, and let  $B_1, B_2, \dots, B_i$  be arbitrary Borel sets in  $V$  of positive measure. Let  $f_1, f_2, \dots, f_i$  be linearly independent continuous functions orthogonal to the constant function. Then there are some constants  $c_0, c_1, \dots, c_i$  such that the function  $f = c_0 + \sum_{j=1}^i c_j f_j$  is not constant and has the following property:

For each  $j = 1, \dots, i$ , both intersections  $B_j \cap f^{-1}((-\infty, 0])$  and  $B_j \cap f^{-1}([0, \infty))$  have volume not less than  $\text{vol}(B_j)/2$ .

**Remark:** When the  $f_j$  are nice smooth functions, the level set  $f^{-1}(0)$  has measure zero, and we get the inequalities

$$\text{vol}(B_j \cap f^{-1}((-\infty, 0])) = \text{vol}(B_j \cap f^{-1}([0, \infty))) = \frac{1}{2} \text{vol}(B_j).$$

**Proof.** The functions  $f_j$  map  $V$  into  $\mathbb{R}^i$ . By the Borsuk-Ulam theorem, there is a hyperplane which divides each  $B_j$  into two pieces of measure  $\geq \text{vol}(B_j)/2$ . This hyperplane is defined by a combination  $c_0 + \sum_{j=1}^i c_j f_j$ .

**Proof of the inequality**  $\lambda_i \geq \varepsilon^{-2} C_2^{1+\varepsilon}$ . Cover  $V$  by  $i = N(\varepsilon)$  balls of radius  $\varepsilon$ . Take the eigenfunctions  $f_1, \dots, f_i$  and form  $f = c_0 + \sum_{j=1}^i c_j f_j$  as above. For each ball  $B_j$ , take the concentric ball  $\tilde{B}_j$  of radius  $2\varepsilon$  and set  $g = f^2$ . Then for each  $j = 1, 2, \dots, i$ , we have

$$\int_{B_j} g \, dv \leq c(n, \varepsilon) \int_{\tilde{B}_j} \|\operatorname{grad} g\| \, dv, \quad (i)$$

where  $c(n, \varepsilon) = 2(b_{n+1}(2\varepsilon) - b_{n+1}(\varepsilon))/a_n(\varepsilon)$ .

**Proof.** Set  $B_j(t) = B_j \cap g^{-1}([t, \infty))$  and  $\tilde{B}_j(t) = \tilde{B}_j \cap g^{-1}([t, \infty))$ . One obviously has (see [Ber–Gau–Maz], for example)

$$\begin{aligned} \int_{B_j} g \, dv &= \int_0^\infty \operatorname{vol}(B_j(t)) \, dt, \\ \int_{\tilde{B}_j} \|\operatorname{grad} g\| \, dv &= \int_0^\infty \operatorname{vol}(\partial \tilde{B}_j(t)) \, dt, \end{aligned}$$

where in the first case, “vol” denotes the  $(n+1)$ -dimensional volume in  $V$ , and in the second formula, we use the  $n$ -dimensional volume of the hypersurface  $\partial \tilde{B}_j(t)$ . In order to prove (i), we must only show that for each noncritical value  $t \in (0, \infty)$ , one has

$$\operatorname{vol}(B_j(t)) \leq c(n, \varepsilon) \operatorname{vol}(\tilde{B}_j(t)).$$

Denote by  $B^+ = B_j^+(t) \subset B_j(t)$  the set where  $f \geq 0$  and denote by  $B^- \subset B_j(t)$  the set where  $f \leq 0$ . When  $t > 0$ , these sets are disjoint, and their volumes do not exceed  $\operatorname{vol}(B_j(t))/2$ .

The hypersurface  $\partial \tilde{B}_j(t)$  is also divided according to the sign of  $f$  into two parts which we denote by  $H^+$  and  $H^-$  correspondingly. Let us show that

$$\operatorname{vol}(B^+) \leq c(n, \varepsilon) \operatorname{vol}(H^+).$$

Set  $W_0 = B^+$  and  $W_1 = B_j(t) \setminus B^+$ . For any two points  $w_0 \in W_0$ ,  $w_1 \in W_1$ , the shortest geodesic segment between these points has length at most  $2\varepsilon$ , and it meets  $H^+$  at some point. By applying (C) to  $W_0, W_1$  and to the hypersurface  $f^{-1}(\sqrt{t}) \supset H^+$ , and by applying (B) to  $H^+$ , we get our inequality.

The same argument shows that

$$\operatorname{vol}(B^-) \leq c(n, \varepsilon) \operatorname{vol}(H^-),$$

and by adding the two inequalities, we obtain our estimate for  $\operatorname{vol}(B_j(t))$  and hence for  $\int_{B_j} g \, dv$ .

Denote by  $M$  the maximal multiplicity of the covering  $\{\tilde{B}_j\}_{1,2,\dots,i}$ . This number  $M$  satisfies

$$M \leq M_n(\varepsilon) = b_{n+1} \left( \frac{13}{2} \varepsilon \right) (b_{n+1}(\varepsilon/2))^{-1}.$$

Really, take a point  $v \in V$  which is contained in  $M$  balls  $\tilde{B}_j$ . The ball  $B_{2\varepsilon}$  of radius  $2\varepsilon$  around  $v$  contains  $M$  centers of the balls  $B_j$ . But the ball  $B_{3\varepsilon}$  around  $v$  can be covered by  $p \leq M_n(\varepsilon)$  balls of radius  $\varepsilon$ , and the inequality  $M > p$  would contradict the minimality of the covering  $\{B_j\}$ . (The definition of  $N(\varepsilon)$  implies that  $V$  cannot be covered by  $N(\varepsilon) - 1$  balls of radius  $\varepsilon$ .) Now we have

$$\begin{aligned} \int_V g \, dv &\leq \sum_{j=1}^i \int_{B_j} g \, dv \\ &\leq c(n, \varepsilon) \sum_{j=1}^i \int_{\tilde{B}_j} \|\operatorname{grad} g\| \, dv \\ &\leq M_n(\varepsilon) c(n, \varepsilon) \int_V \|\operatorname{grad} g\| \, dv. \end{aligned}$$

We now recall that  $g = f^2$ , and hence

$$\int_V \|\operatorname{grad} g\| \, dv \leq 2 \left( \left( \int \|\operatorname{grad} f\|^2 \, dv \right) \left( \int f^2 \, dv \right) \right)^{1/2}.$$

So we have

$$\int_V f^2 \, dv \leq E \int_V \|\operatorname{grad} f\|^2 \, dv,$$

where  $E = 4(M_n(\varepsilon)c(n, \varepsilon))^2$ .

The function  $f$  was constructed as a combination  $f = c_0 + \sum_{j=1}^i c_j f_j$ , where one of the  $c_j$ ,  $j > 0$ , is different from zero and where the eigenfunctions  $f_i$  can be assumed to be orthonormal. So, we have

$$\begin{aligned} \int_V f^2 \, dv &= \sum_{j=0}^i c_j^2, \\ \int_V \|\operatorname{grad} f\|^2 \, dv &= \sum_{j=1}^i \lambda_j c_j^2, \end{aligned}$$

and so

$$\sum_{j=0}^i c_j^2 \leq E \sum_{j=1}^i \lambda_j c_j^2.$$

Because one of the  $c_j$ ,  $j > 0$ , is nonzero, one of the numbers  $\lambda_j$  must be at least  $E^{-1}$ , and hence, the largest eigenvalue  $\lambda_i$  satisfies

$$\lambda_i \geq E^{-1}.$$

We recall that  $E = 4(M_n(\varepsilon)c(n, \varepsilon))^2$ , where

$$M_n(\varepsilon) = b_{n+1} \left( \frac{13}{2} \varepsilon \right) (b_{n+1}(\varepsilon/2))^1,$$

$$c(n, \varepsilon) = 2 \frac{b_{n+1}(2\varepsilon) - b_{n+1}(\varepsilon)}{a_n(\varepsilon)},$$

and  $b_{n+1}(\varepsilon)$  denotes the volume of the  $(n+1)$ -dimensional hyperbolic ball and  $a_n(\varepsilon)$  denotes the volume of its boundary. So, for a sufficiently small  $C_2 = C_2(n)$ , we have

$$\lambda_i \geq \varepsilon^{-2} C_2^{1+\varepsilon}.$$

**Proof of the inequality**  $\lambda_i \leq \varepsilon^{-2} C_1^{1+\varepsilon}$ . Let  $V$  be any manifold. In order to show that  $\lambda_i \leq \lambda$ , it is sufficient, according to the variational principle, to find  $2i$  nonzero functions  $\psi_1, \dots, \psi_{2i}$  on  $V$  with the following properties.

(a) The supports of the  $\psi_i$  are pairwise disjoint.

(b)  $\int_V \psi_j^2 dv \geq \lambda \int \|\operatorname{grad} \psi_j\|^2$ ,  $j = 1, \dots, 2i$ .

When  $i = N(\varepsilon)$ , one can always find  $2i$  disjoint balls  $B_j$  in  $V$  of radius  $\varepsilon/5$ . With each ball  $B_j$  with center  $v_j \in B_j$ , we associate a function  $\psi_i$  defined as follows.

$$\psi_j = \psi_j(v) = \{\operatorname{dist}(v_j, v) - 1/5, v \in B_j, 0, v \notin B_j.\}$$

One obviously has

$$\int_V \|\operatorname{grad} \psi_j\|^2 dv = \operatorname{vol}(B_j).$$

Denote by  $\tilde{B}_j \subset B_j$  the concentric ball of radius  $\varepsilon/10$ . One has

$$\int_V \psi_j^2 dv \geq \frac{\varepsilon^2}{100} \operatorname{vol} \tilde{B}_j.$$

When  $R(V) \geq -n$ , we know that  $\operatorname{vol}(B_j)/\operatorname{vol}(\tilde{B}_j) \leq b_{n+1}(\varepsilon/5)/b_{n+1}(\varepsilon/10)$ , and so we get

$$\lambda_i \leq 100 \varepsilon^{-2} \frac{b_{n+1})(\varepsilon/5)}{b_{n+1}(\varepsilon/10)} \leq \varepsilon^{-2} C_1^{1+\varepsilon}.$$

Notice that the argument we used above is close to the considerations of Cheeger (see [Che]RBLD) and Yau (see [Yau]ICFE).

**Final remarks.** Our lower estimate for  $\lambda_i$  can also be stated as follows.

There exists a constant  $C = C_n$  such that for any closed  $(n + 1)$ -dimensional manifold  $V$  with  $R(V) \geq -n\delta$ ,  $\delta \geq 0$ , and  $\text{diam } V \leq D$ , the  $i$ -th eigenvalue  $\lambda_i$  satisfies

$$\lambda_i \geq D^{-2} C^{1+D\sqrt{\delta}} i^{2/(n+1)}.$$

On the other hand, the asymptotics of  $\lambda_i$  when  $i \rightarrow \infty$  depends only on the volume  $\text{vol}(V)$ . It would be interesting to find a theorem interpolating between these two facts. The following remark indicates one possibility.

Let  $V$  be as above and suppose that the fundamental group of  $V$  is infinite and has no torsion. Denote by  $\ell$  the length of the shortest noncontractible loop. Then one has

$$\text{If } i \geq (D/\ell)^n \exp(2nD + 2n), \text{ then } \lambda_i \geq (D^n \ell)^{-2/(n+1)} C_n^{1+D\sqrt{\delta}} i^{2/(n+1)}.$$

**Proof.** We must estimate from above the number  $N(\varepsilon)$ ,  $\varepsilon \leq \ell$ . Take the universal covering  $\pi : \tilde{V} \rightarrow V$  and a point  $\tilde{v} \in \tilde{V}$  such that the shortest loop in  $V$  passes through  $\pi(\tilde{v}) \in \tilde{V}$ . Consider the ball  $\tilde{B} \subset \tilde{V}$  of radius  $2D$  centered at  $\tilde{v}$ . One can easily see that for each  $v \in V$ , the set  $f^{-1}(v) \cap \tilde{B}$  contains at least  $q \geq D\ell^{-1}$  points, and for any two distinct points  $\tilde{v}_1, \tilde{v}_2 \in f^{-1}(v)$ , one has  $\text{dist}(\tilde{v}_1, \tilde{v}_2) \geq \ell$ .

When  $R(V) \geq -n$ , each  $\varepsilon$ -neighborhood of  $\tilde{B}$  contains at most  $N \leq b_{n+1}(2D+\varepsilon)/b_{n+1}(\varepsilon)$  disjoint balls of radius  $\varepsilon$ , and when  $\varepsilon < \ell$ , we conclude that  $V$  itself has at most  $N/\ell$  such balls. It follows that  $V$  can be covered by  $N_1 \leq N/\ell$  balls of radius  $2\varepsilon$ . This is exactly the estimate we need for the case  $\delta = 1$ , and by scaling the metric in  $V$  by  $\sqrt{\delta}$ , we reduce the general case to  $\delta = 1$ .

Notice also that for manifolds with pinched sectional curvature, P. Buser (see [Buser]) obtained much sharper results by dividing  $V$  into the pieces which are not necessarily balls, but still have a sufficiently simple geometry.

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## Appendix D

# Systolically Free Manifolds

by Mikhail Katz<sup>1</sup>

This appendix fits in with Chapter 4, Section E<sub>+</sub>, paragraph 4.45 “*On higher dimensional systoles*” (p. 264). The  $k$ -systole of a Riemannian manifold  $X$  is, roughly, the least volume of a  $k$ -dimensional non-nullhomologous submanifold of  $X$ . See paragraph 4.40 of the same section (p. 260) for a definition. A more detailed updated account of systolic freedom appears in [Katz-Suc].

The existence of a systolic inequality will mean that the volume of  $X$  imposes a constraint on systoles, as in Loewner’s Theorem 4.1 and Gromov’s Theorem 4.41.

We will refer to the absence of systolic inequalities as “systolic freedom.” To exhibit the freedom of a manifold  $X$ , we will construct families of metrics on  $X$  whose systoles are not constrained by the volume.

There are two rather different systolic problems: one involving a pair of systoles of distinct complementary dimensions, and one involving the middle-dimensional systole.

The idea for the pair of complementary dimensions is as follows. Let  $k < \frac{n}{2}$  where  $n = \dim(X)$ . Following M. Gromov (see [Berger]Sys, p. 306 and [Gro]SII section 4.A<sub>5</sub>, p. 354), we use Thom’s theorem (see [Thom]) to choose a  $k$ -dimensional submanifold with the following two properties: (a) its normal bundle is trivial; (b) its connected components generate (rationally) the homology group  $H_k(X)$ .

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The construction takes place within a fixed trivialized tubular neighborhood of the submanifold. Gromov described an expansion-contraction procedure (see [Gro]MIKM, section 2) with the desired effect on the systole of the complementary dimension  $n-k$ . We combine the expansion-contraction with a volume-saving twist.

In more detail, Thom's theorem allows us to carry out the expansion-contraction procedure in a neighborhood of a suitable  $k$ -dimensional submanifold described above. The resulting metrics have large  $(n-k)$ -dimensional systole (compared to the volume). So far the  $(k, n-k)$  systolic inequality is not violated. This is because the metric is essentially a product and the volume is too large. To decrease the volume, we introduce a nondiagonal term in the Riemannian metric. The key idea is due to Gromov and is described in paragraph 4.45 for the product of a circle by a simply connected manifold admitting a free circle action. Generalizing the construction requires a splitting of both the  $k$ -dimensional class and its tubular neighborhood (see below). It is at this point that the modulo 4 condition on  $k$  comes in.

**D.1. Theorem ([Bab–Katz]):** *Let  $X$  be an orientable  $(k-1)$ -connected  $n$ -dimensional manifold, where  $n \geq 3$  and  $k < \frac{n}{2}$ . Suppose  $k$  is not a multiple of 4. Then*

$$\inf_g \frac{\text{vol}(g)}{\text{sys}_k(g) \text{sys}_{n-k}(g)} = 0, \quad (1)$$

where the infimum is taken over all metrics  $g$  on  $X$ .

In the middle-dimensional case, we have the following general result.

**D.2. Theorem ([Bab–Katz–Suc]):** *Let  $X$  be a manifold of dimension  $n = 2m$ , where  $m \geq 3$ . Suppose the group  $H_m(X)$  is torsion free. Then*

$$\inf_g \frac{\text{vol}(g)}{\text{sys}_m^2(g)} = 0, \quad (2)$$

where the infimum is taken over all metrics on  $X$ .

One may ask if systolic freedom persists if one restricts the class of competing metrics to homogeneous ones. We have the following partial result in this direction.

**D.3. Theorem:** *The manifold  $S^3 \times S^3$  satisfies*

$$\inf_g \frac{\text{vol}_6(g)}{\text{sys}_3^2(g)} = 0, \quad (3)$$

where the infimum is taken over homogeneous metrics  $g$  on  $S^3 \times S^3$ .

A key technical result in the proof of Theorem 1 is the following lemma, inspired by Gromov’s first example of free metrics on  $S^1 \times S^3$  (see 4.45 and [Berger]Sys).

**D.4. Lemma ([Ber–Katz]II,[Bab–Katz]):** *Consider the cylinder  $M = T^1 \times I$ , circle  $C$ , and the manifold  $Y = C \times M = T^2 \times I$ . We view  $M$  as a relative cycle in  $H_2(Y, \partial Y)$ . Then*

$$\inf_g \frac{\text{vol}(g)}{\text{sys}_1(g) \text{mass}_2([M])} = 0. \quad (4)$$

Here the infimum is taken over all metrics whose restriction to each component of the boundary  $\partial Y = T^2 \times \partial I$  is the standard “unit square” torus satisfying  $\text{length}(C) = \text{length}(T^1) = 1$ . The 2-mass of the class  $[M]$  is the infimum of areas of rational cycles representing it.

**Proof.** The metric of the universal cover  $p : \mathbb{R}^3 \rightarrow N$  of the standard nilmanifold  $N$  of the Heisenberg group can be written as

$$(dz - xdy)^2 + dy^2 + dx^2. \quad (5)$$

We will use it to construct a sequence of metrics  $(g_j)$ ,  $j \in \mathbb{N}$ , on  $Y$  with the required asymptotic behavior. An alternative approach using a solvable group was used in [Pit].

The restriction of the above metric to the parallelepiped defined by the inequalities  $0 \leq x \leq j$ ,  $0 \leq y \leq 1$ ,  $0 \leq z \leq 1$  defines a metric on  $[0, j] \times T^1 \times C$  once we identify the opposite sides of the unit square in the  $y, z$  plane. Here  $[0, j]$  is parameterized by  $x$ , the circle  $T^1$  by  $y$ , and the circle  $C$  by  $z$ . The covering projection  $p$  induces a monomorphism

$$p_* : \pi_1([0, j] \times T^2) \rightarrow \pi_1(N) \quad (6)$$

from  $\mathbb{Z}^2$  to the group of unipotent integer  $3 \times 3$  matrices.

The metric on  $[0, j] \times T^2$  does not satisfy the boundary condition (specified in the statement of the lemma) at  $x = j$ , since  $\text{length}(\{j\} \times T^1) = \sqrt{1 + j^2}$ . We correct this by taking its “double” using a mirror placed at  $x = j$ . In other words, let  $I = [0, 2j]$ , let  $X = \min(x, 2j - x)$ , and consider the sequence of metrics on  $Y = T^2 \times I$  defined by

$$g_j = (dz - Xdy)^2 + dy^2 + dx^2. \quad (7)$$

Note that the projection  $p$  extends over  $Y$ , so that we still have the monomorphism  $p_*$  of fundamental groups.

Let us show that the growth of  $\text{mass}_2[M]$  is quadratic in  $j$ . Let  $\phi_j(x)$  be a partition of unity-type function with support in  $[0, j]$ , and such that

$\phi_j(x) = 1$  for  $x \in [1, j-1]$ . We define a 2-form  $\alpha = \alpha_j$  by setting

$$\alpha = \frac{\phi_j(x)}{\sqrt{1+x^2}} * (dz) \quad (8)$$

where  $*$  is the Hodge star of the metric  $g_j$ . Let us check that  $\alpha$  is a calibrating form, i.e.,  $\|\alpha\| = 1$  and  $d\alpha = 0$ .

By definition of  $g_j$  the 1-forms  $dx$ ,  $dy$ , and  $dz - xdy$  form an orthonormal basis. Therefore  $\|dz\|_{(x,y,z)} = \|(dz - xdy) + xdy\| = \sqrt{1+x^2}$ . Thus  $\|\alpha\| = 1$ . Furthermore,

$$*(dz) = dx \wedge dy - xdx \wedge (dz - xdy) = dx \wedge ((1+x^2)dy - xdz). \quad (9)$$

Let  $a_j = \int_M \alpha = \int_M \phi_j(x) \sqrt{1+x^2} dx \wedge dy = \int_0^j \phi_j(x) \sqrt{1+x^2} dx$ . Thus  $a_j$  grows as  $j^2$ . The calculation (9) shows that the 2-form  $\alpha$  is closed. Hence by Stokes,

$$\text{mass}_2[M] \geq \int_M \alpha = a_j, \quad (10)$$

and the growth of  $\text{mass}_2[M]$  is quadratic.

Meanwhile, the injectivity of  $p_*$  of (6) allows us to conclude that  $\text{sys}_1(g_j) \geq \pi \text{sys}_1(N)$ , where  $\pi \text{sys}_1$  is the length of the shortest noncontractible curve. Hence the 1-systole is uniformly bounded from below in  $j$ . The volume of the Riemannian submersion  $(Y, g_j) \rightarrow [0, 2j]$  with fiber of unit area is  $2j$ . Thus

$$\frac{\text{vol}(g_j)}{\text{sys}_1(g_j) \text{mass}_2[M]} = O\left(\frac{1}{j}\right), \quad (11)$$

proving the lemma.

**Proof of Theorem D.1.** The idea was described at the beginning of the appendix. Let  $e_1, \dots, e_b$  be an integral basis for a maximal lattice in  $H_k(X, \mathbb{Z}) = \mathbb{Z}^b + \text{torsion}$ . We will exhibit a  $k$ -dimensional submanifold  $A \subset X$  whose connected components  $A_1, \dots, A_b$  have the following properties:

- (i) each  $A_i$  is diffeomorphic to  $S^{k-1} \times C$  where  $C$  is a circle;
- (ii) the classes  $[A_i]$  satisfy  $[A_i] = 2e_i$ ;
- (iii) the normal bundle  $\nu$  of  $A_i \subset X$  is trivial.

By Hurewicz's theorem, we find  $k$ -spheres  $f_i : S^k \rightarrow X$ ,  $i = 1, \dots, b$  satisfying (ii). Since the total Stiefel-Whitney class  $w(S^k) = 1$  is trivial, we have

$$w_k[f_i^*(\nu)] = w_k[f_i^*(TX)] = w_k(TX)(f_*[S^k]) = w_k(TX)(2e_i), \quad (12)$$

and so  $w_k[f_i^*(\nu)] = 2w_k(TX)(e_i) = 0 \in H^0(X, \mathbb{Z}_2)$ .

By real Bott periodicity, there is at most a  $\mathbb{Z}_2$ 's worth of inequivalent bundles of rank  $\geq k+1$  over  $S^k$  for  $k \neq 0 \pmod{4}$ , distinguished by the class  $w_k$ . Hence  $\nu$  is trivial. We now perform a surgery inside  $X$  by attaching a handle to each imbedded sphere  $f_i(S^k)$ , turning it into a product  $A_i = C \times S^{k-1}$  where  $C$  is a circle, still with trivial normal bundle. Thus a tubular neighborhood of  $A_i$  splits as a product

$$A_i \times B^{n-k}. \quad (13)$$

Let  $R \subset B^{n-k}$  be any submanifold of codimension 2 with trivial normal bundle. The boundary of its tubular neighborhood is diffeomorphic to  $R \times T^1$ , and we obtain a hypersurface

$$\Sigma_i = A_i \times R \times T^1 = C \times S^{k-1} \times R \times T^1 = T^2 \times L \quad (14)$$

in a neighborhood of  $A_i \subset X$ , where  $T^2 = C \times T^1$  is a 2-torus and  $L = S^{k-1} \times R$ .

Let  $\Sigma \subset X$  be the disjoint union of such hypersurfaces  $\Sigma_1, \dots, \Sigma_b$ . A tubular neighborhood of  $\Sigma \subset X$  is a disjoint union of open submanifolds  $\Sigma_i \times I = C \times T^1 \times L \times I$ . What happens metrically can be described as follows. We choose a metric on  $X$  which is a direct sum in a neighborhood of each  $\Sigma_i$ , with four summands

$$C \times T^1 \times L \times I \subset X, \quad (15)$$

where  $C$  and  $T^1$  are of unit length,  $L$  has unit volume, and  $I$  is an interval. Denote by  $X_0$  the resulting Riemannian manifold. We now modify the direct sum metric on

$$C \times T^1 \times L \times I = Y \times L \quad (16)$$

by using the metrics  $g_j$  on  $Y = C \times T^1 \times I$  of Lemma D.4, while  $L$  remains a direct summand. Denote by  $X_j$  the resulting Riemannian manifold. The boundary condition of Lemma D.4 ensures that the new metric on  $X$  varies continuously across the boundary  $T^2 \times L \times \partial I$ .

**Proposition 1.** *The systole  $\text{sys}_k(X_j)$  is uniformly bounded from below in  $j$ .*

**Proof.** Let  $z$  be a  $k$ -cycle in  $X_j$ ,  $[z] \neq 0$  in  $H_k(X_j)$ . If the support of  $z$  lies outside  $\Sigma \times I$ , then whether  $[z]$  has finite or infinite order, we have

$$\text{vol}_k(z \subset X_j) = \text{vol}_k(z \subset X_0) \geq \text{sys}_k(X_0), \quad (17)$$

yielding a lower bound independent of  $j$ . If  $z$  lies in  $\Sigma \times I$ , then its class  $[z]$  lies in the span of  $[A_1], \dots, [A_b]$ , so that  $[z] = \lambda_1[A_1] + \dots + \lambda_b[A_b]$ . Here one of the coefficients is nonzero, say  $\lambda_l$ . Let

$$\pi : Y \times L \rightarrow S^{k-1} \quad (18)$$

be the projection to the first factor of  $L = S^{k-1} \times R$ . By the coarea inequality,

$$\text{vol}_k(z) \geq \int_{S^{k-1}} \text{length}(z \cap \pi^{-1}(t)) dt \geq \int_{S^{k-1}} \text{sys}_1(g_j) dt \geq \pi \text{sys}_1(N), \quad (19)$$

also yielding a lower bound  $\text{sys}_k(\Sigma \times I) \geq \pi \text{sys}_1(N)$  independent of  $j$ .

Here we must verify that the 1-cycle  $z \cap \pi^{-1}(t)$  represents a nonzero class in  $\pi^{-1}(t) = (Y, g_j) \times R$ . This is so because the set-theoretic formula

$$(C \times S^{k-1}) \cap (Y \times R) = C \quad (20)$$

makes sense at the homological level. Indeed, inside  $\Sigma_l \times I = Y \times L$  we have

$$\begin{aligned} [z] \smile [Y \times R] &= \lambda_l[A_l] \smile [Y \times R] = \lambda_l[C \times S^{k-1}] \smile [Y \times R] \\ &= \lambda_l[(C \times S^{k-1}) \cap (C \times T^1 \times I \times R)] = \lambda_l[C] \neq 0, \end{aligned}$$

where  $\smile$  is the homological operation (dual to cup product in cohomology) pairing the groups  $H_k(\Sigma_l \times I)$  and  $H_{n-k+1}(\Sigma_l \times I, \Sigma_l \times \partial I)$ . This operation is realized by transverse intersection of representative cycles, and hence  $[z \cap \pi^{-1}(t)] \neq 0$ .

For general  $z$  we argue as follows. Assume for simplicity that  $b_k(X) = 1$ . We will cut  $z$  at a narrow place and replace it by the sum of two cycles, each of which can be handled as above. If  $b_k > 1$ , we have to make several cuts, but the rest of the argument is the same.

We argue by contradiction. Suppose  $X_j$  contains a  $k$ -cycle  $z_j$  such that

$$\lim_{j \rightarrow \infty} \text{vol}_k(z_j) = 0. \quad (22)$$

Let  $d: X_j \rightarrow [0, 2j]$  be the map extending the  $x$ -coordinate of Lemma D.4 by collapsing the components of the complement

$$X \setminus (\Sigma \times I) \quad (23)$$

to the respective endpoints. By the coarea inequality, we find points  $x_- \in [0, 1] \subset I$  and  $x_+ \in [2j-1, 2j] \subset I$  such that

$$\text{vol}_{k-1}(z \cap d^{-1}(x_\pm)) \rightarrow 0 \quad (24)$$

as  $j \rightarrow \infty$ . Let  $\gamma_{\pm} = z \cap d^{-1}(x_{\pm})$ . Since  $\text{vol}_{k-1}(\gamma_{\pm}) = o(1)$ ,  $\gamma_{\pm}$  can be filled in by a  $k$ -chain  $D_{\pm}$  with  $\text{vol}_k(D_{\pm}) = o(1)$ . This follows from the isoperimetric inequality for small cycles proved in [Gro]FRM, Sublemma 3.4.B'. Since  $\partial D_{\pm} = \gamma_{\pm}$ , we can write  $z_j = z' + z''$  where  $z' = z \cap d^{-1}([x_-, x_+]) + D_+ - D_-$  is a  $k$ -cycle in  $\Sigma \times I$ . Now

$$\begin{aligned}\text{vol}_k(z_j) &\geq \min(\text{vol}_k(z'), \text{vol}_k(z'')) - \text{vol}_k(D_+ + D_-) \\ &\geq \min(\text{sys}_k(X_1), \text{sys}_k(\Sigma \times I)) - o(1) \\ &\geq \min(\text{sys}_k(X_1), \pi \text{sys}_1(N)) - o(1)\end{aligned}$$

providing a lower bound independent of  $j$ .

**D.5. Lemma:** *Let  $X_j$  be the Riemannian manifold constructed above. Then the  $(n-k)$  systole  $\text{sys}_{n-k}(X_j)$  grows quadratically in  $j$ .*

**Proof.** Let  $\alpha_i$  be the 2-form of Lemma D.4 with support in a neighborhood of  $A_i$ . We use the calibrating form

$$\beta_i = \alpha_i \wedge \text{vol}_R \quad (26)$$

where  $\text{vol}_R$  is the volume form of the codimension 2 submanifold  $R \subset B^{n-k}$ . Note that  $H_{n-k}(X)$  is torsion free as  $H_{k-1}(X) = 0$  by hypothesis of Theorem D.1. Using Poincaré duality, we choose integer  $(n-k)$ -cycles  $M_1, \dots, M_b$  which define a basis of  $H_{n-k}(X, \mathbb{Z})$  “dual” to the basis  $e_1, \dots, e_b$  of  $H_k(X, \mathbb{Z})$ , so that the algebraic intersections satisfy

$$[M_i] \cap e_h = \delta_{ih} \quad (27)$$

and therefore  $M_i \cap A_h = 2\delta_{ih}$ . We may assume that all intersections of  $M_i$  and  $A_h$  are transverse and moreover standard, so that  $M_i \cap (\Sigma_h \times I)$  is a disjoint union of copies of  $M \times R$  where  $M = T^1 \times I$  is the cylinder of Lemma D.4. Hence  $\int_{M \times R} \beta_i = \pm a_j$ , where  $a_j = \int_M \alpha_j$  (cf. Lemma D.4), for each connected component  $M \times R$  of  $M_i \cap (\Sigma_h \times I)$ . In particular

$$\int_{M_i \cap (\Sigma_h \times I)} \beta_i = 0 \text{ if } i \neq h. \quad (28)$$

Finally, let  $m \in H_{n-k}(X)$  be a nonzero class. Let  $m = \epsilon_1 d_1[M_1] + \dots + \epsilon_b d_b[M_b]$  where  $\epsilon_i = \pm 1$  and  $d_i \geq 0$ . We use the signs  $\epsilon_i$  to specify a suitable calibrating form  $\beta$  by setting

$$\beta = \epsilon_1 \beta_1 + \dots + \epsilon_b \beta_b. \quad (29)$$

Now

$$\begin{aligned}
 \text{mass}_{n-k}(m) &\geq \int_m \beta = \sum_{i=1}^b \epsilon_i d_i \int_{M_i} \beta = \sum_i \epsilon_i d_i \int_{M_i} (\Sigma_h \epsilon_h \beta_h) \\
 &= \sum_i \epsilon_i^2 d_i \int_{M_i} \beta_i \quad (\text{by 53}) \\
 &= \sum_i d_i \int_{M_i} \beta_i = \sum_i d_i 2a_j \geq a_j
 \end{aligned} \tag{30}$$

since  $m \neq 0$ , where  $a_j = \int_M \alpha_j$  grows quadratically in  $j$ . Hence the growth of  $\text{sys}_{n-k}(X_j)$  is quadratic in  $j$ .

Now Propositions 1 and 2 and the linear growth of the volume of  $X_j$  yield

$$\frac{\text{vol}(X_j)}{\text{sys}_k(X_j) \text{mass}_{n-k}(X_j)} = O\left(\frac{1}{j}\right). \tag{31}$$

This completes the proof of Theorem D.1.

We now prove some preliminary results for Theorem D.2, in the form of steps 1 through 4.

*Step 1.* A  $(2m - 1)$ -dimensional complex admits a map to the bouquet of  $m$ -spheres which induces monomorphism in  $m$ -dimensional homology with rational coefficients.

**Proof.** Let  $K^i$  be the  $i$ -skeleton of the complex  $K$ . From the exact sequence of the pair  $(K, K^{m-1})$ , we see that the homomorphism  $H_m(K) \rightarrow H_m(K/K^{m-1})$  is injective. This reduces the problem to the case when  $K$  is  $(m-1)$ -connected. Now let  $b_m = b_m(K)$  and let  $H_m(K) \rightarrow \mathbb{Z}^{b_m}$  be the quotient by the torsion subgroup. Let  $f : X \rightarrow K(\mathbb{Z}^{b_m}, m)$  be the associated map to the Eilenberg-MacLane space. Now  $K(\mathbb{Z}^{b_m}, m) = (K(\mathbb{Z}, m))^{b_m}$  and  $K(\mathbb{Z}, m)$  admits a cell structure with no cells in dimension  $m + 1$ . Hence by the cellular approximation theorem, we obtain a map from the  $(m+1)$ -skeleton of  $K$  to the bouquet  $\vee S^m$  of  $b_m$  spheres  $S^m$ , injective on nontorsion  $m$ -dimensional homology classes. We now proceed as in [Serre]GH (page 278 and 287–288). Here an induction on skeleta uses self-maps of the bouquet  $\vee S^m$  which annihilate all relevant homotopy. By Eckmann's theorem [Eck], a self map  $f_q$  of degree  $q$  of the sphere  $S^m$  induces multiplication by  $q$  in the (stable) finite group  $\pi_i(S^m)$  for  $m + 1 \leq i \leq 2m - 2$ . By Hilton's theorem, we have a splitting of the stable homotopy groups for a bouquet. Let  $g : K^i \rightarrow \vee S^m$  be a map defined on the  $i$ -skeleton. Then  $f_q \circ g$  extends to the  $(i+1)$  skeleton if  $q$  is a multiple of the order of the finite group  $\pi_i(S^m)$ .

*Step 2.* A bouquet of  $m$ -spheres admits a self-map which induces a homomorphism of the first unstable group whose image is contained in the subgroup generated by Whitehead products.

**Proof.** For a single  $m$ -sphere, we argue as follows. Let  $G \subset \pi_{2m-1}(S^m)$  be the subgroup generated by the Whitehead product  $[e, e]$  where  $e$  is the fundamental class of the sphere. Then  $G$  is precisely the kernel of the suspension homomorphism

$$E: \pi_{2m-1}(S^m) \rightarrow \pi_{2m}(S^{m+1}). \quad (32)$$

Since  $E$  commutes with  $f_q$ , it suffices to choose  $q$  to be the order of the group  $\pi_{2m}(S^{m+1})$ . For a bouquet  $\vee_i S_i^m$ , let  $e_i$  be the fundamental class of  $S_i^m$ . By Hilton's theorem, the group  $\pi_{2m-1}(\vee_i S_i^m)$  modulo mixed Whitehead products  $[e_i, e_j]$  for  $i \neq j$  is just

$$\oplus_i \pi_{2m-1}(S_i^m). \quad (33)$$

Hence the same argument applies.

If we start with a  $2m$ -manifold represented as a CW complex with a single  $2m$ -cell, we can apply Steps 1 and 2 to its  $(2m-1)$  skeleton  $K^{2m-1}$  to construct a suitable map to the bouquet  $\vee S^m$ . We can now proceed in two different ways: (a) either by eliminating all homotopy of the bouquet (at least rationally) in dimension  $2m-1$ , or, more economically, (b) eliminating just enough to allow the map to extend across the  $2m$ -cell. Described below is the first approach.

**D.6. Definition:** A  $2m$ -dimensional complex is “free” if

$$\inf_g \frac{\text{vol}_{2m}(g)}{\text{sys}_m^2(g)} = 0, \quad (34)$$

where the infimum is taken over all metrics  $g$ .

*Step 3.* Consider a  $2m$ -dimensional complex  $X$  obtained from a bouquet of  $m$ -spheres by attaching  $b$  copies of a  $2m$ -cell. If the closure of each  $2m$ -cell is free, then  $X$  is free.

**Proof.** One chooses the following representative  $X_0$  in the homotopy class of  $X$ . We take the Cartesian product of the bouquet  $\vee S^m$  with the bouquet of  $b$  intervals of sufficiently big length  $l$ . Here each interval corresponds to a  $2m$ -cell. Each  $2m$ -cell is then attached at the end of its interval. We choose free metrics of the same volume on each cell closure. The freedom of  $X$  reduces to obtaining a lower bound on the  $m$ -volume of a cycle  $z$  in

$X_0$ . This is done as follows. Suppose for simplicity that there are only two  $2m$ -cells, attached at either end of the cylinder

$$\vee S^m \times [0, l] \quad (35)$$

(for  $l$  to be chosen later). We use the coarea inequality to find a narrow place and cut  $z$  into two pieces along an  $(m-1)$ -cycle  $\gamma = z \cap p^{-1}(x)$ . Here  $p : \vee S^m \times [0, l] \rightarrow [0, l]$  is the projection to the second factor. The point  $x \in [0, l]$  is chosen so that

$$\text{vol}_{m-1}(\gamma) \leq \frac{1}{l} \text{vol}_m(z). \quad (36)$$

It remains to “fill in” the cycle  $\gamma$ . This can be done by the isoperimetric inequality for cycles of small volume ([Gro]FRM, Sublemma 3.4.B'). Here  $l$  is chosen sufficiently big so that the inequality would apply to  $\gamma$ .

**D.7. Definition:** Let  $X$  and  $Y$  be  $2m$ -dimensional manifolds. A “meromorphic map” from  $X$  to  $Y$  is a continuous map from  $X$  to a CW complex obtained from  $Y$  by attaching cells of dimension at most  $2m-1$ , inducing monomorphism in middle-dimensional homology.

**Example:** Let  $X$  be a complex surface and  $\hat{X} \rightarrow X$  its blow-up at a point  $p \in X$ . Then the classical meromorphic map  $X \rightarrow \hat{X}$  can be modified in a neighborhood of  $p$  and extended to a continuous map from  $X$  to  $\hat{X} \cup_f B^3$  where the 3-ball is attached along the exceptional curve.

*Step 4.* The complex obtained by ‘glueing in’ a single Whitehead product is free if  $m \geq 3$ .

**Proof.** For a “mixed” Whitehead product  $[e_i, e_j]$ , we obtain that  $(S^m \vee S^m) \cup_{[e_i, e_j]} B^{2m} = S^m \times S^m$ , which is free by [Katz].

Consider the complex  $P$  defined by

$$P = S^m \cup_{[e, e]} B^{2m}, \quad (37)$$

where  $e$  is the fundamental class of  $S^m$ . The idea is to construct a “meromorphic map” from  $P$  to the product of spheres, using multiplicative structure in the algebra of homotopy groups. Let  $a$  and  $c$  be the generators of  $H_m(S^m \times S^m)$ , so that  $[a, c] = 0$ . We now attach an  $(m+1)$ -cell along the diagonal  $a + c$ . Let

$$W = S^m \times S^m \cup_{a+c} B^{m+1}, \quad (38)$$

so that  $a = -c$  in  $W$ . Let  $f : S^m \rightarrow W$ ,  $e \mapsto a$ . Then

$$f([e, e]) = [a, a] = [a, -c] = 0, \quad (39)$$

and so the map extends to  $P \rightarrow W$ . We pull back to  $P$  the free metrics on  $W$ . Here the cell added to  $S^m \times S^m$  does not affect the  $(2m)$ -dimensional volume (to obtain a positive definite metric on  $P$ , we increase slightly the pullback of the quadratic form, using the convexity of the cone of positive quadratic forms). This proves the freedom of  $P$  once we know that of  $S^m \times S^m$ .

**Proof of Theorem D.2.** Let  $X$  be any CW complex of dimension  $2m$ . We map its  $(2m-1)$ -skeleton  $K$  to a bouquet as in Step 1. By Step 2, we can assume that the elements of  $\pi_{2m-1}(K)$  are mapped to the subgroup  $G$  generated by (finitely many) Whitehead products in the bouquet. We attach a  $2m$ -cell to this bouquet for each generator of  $G$ . The resulting space is free by Steps 3 and 4. Now the map from  $K$  extends to  $X$ . It follows that  $X$  is free as well.

**Remark:** The proof can be simplified in the case of projective planes  $\mathbb{H}P^2$  and  $CaP^2$ . It relies on the following proposition.

**D.8. Proposition:** *Let  $F$  be  $\mathbb{C}$ ,  $\mathbb{H}$  or  $Ca$ , and let  $m = \dim(F)$ . Consider the map of degree  $q$  from  $FP^1$  to the first component of  $S^m \times S^m$ , to which we glue an  $(m+1)$ -ball along the diagonal sphere. Then the map extends to the projective plane  $FP^2$  if and only if  $q$  is a multiple of*

$$2 \operatorname{tor}(\pi_{2m-1}(FP^1)), \quad (40)$$

where  $\operatorname{tor}$  is the order of the torsion subgroup, equal to 1, 12, or 120 respectively when  $F$  is  $\mathbb{C}$ ,  $\mathbb{H}$ , or  $Ca$ .

**Proof of Theorem D.3.** The metrics we use are Riemannian submersions over a round 2-sphere, where the fiber is Gromov's left-invariant metric on  $S^1 \times S^3$  which was the first example of systolic freedom. To describe free left-invariant metrics on  $S^3 \times S^3$ , it is convenient first to describe some useful coordinates on flat tori of unit area and unit 1-systole. Let  $r \geq 0$ , and consider the metric

$$(dz - rdy)^2 + dy^2 \text{ on } T^2 = \mathbb{R}^2 / \mathbb{Z}^2 = T^1 \times C, \quad (41)$$

and let  $*$  be its Hodge star operator. Here  $T^1$  and  $C$  are parameterized respectively by the  $y$  and  $z$  axes. Note that if  $r$  is an integer, this torus is isometric to the standard "unit square" torus, one of whose sides is the loop  $C$  (what will appear in the sequel is the homothetic metric "square of side  $2\pi$ "). Meanwhile  $\operatorname{length}^2(T^1) = \|\partial/\partial y\|^2 = 1+r^2$ . We set  $R^2 = 1+r^2$ . We have

$$*(dz) = *(dz - rdy) + r*(dy) = dy - r(dz - rdy) = (1+r^2)dy - rdz = R^2 dy - rdz. \quad (42)$$

Now we describe Gromov's metric on  $S^1 \times S^3$  in a way that lends itself to generalization. Let  $S^1 = C$  be the unit circle with the standard 1-form  $dz$ , and let  $b$  be the standard contact 1-form on  $S^3$ . Gromov's metric is then obtained simply by modifying the product metric of a circle of length  $2\pi$  and 3-sphere of radius  $R = \sqrt{1+r^2}$ , by adding a nondiagonal term  $-2rb\,dz$  (symmetric tensor product). Here the Hopf great circles of length  $2\pi R$  play the role of  $T^1$  above. More explicitly, let us complete  $b$  to a basis  $(b, b', b'')$  of 1-forms which is orthonormal with respect to the metric of unit radius, so that  $db = b' \wedge b''$ . Then Gromov's metric is a modification of formula (41):

$$(dz - rb)^2 + b^2 + R^2((b')^2 + (b'')^2). \quad (43)$$

Note that

$$\ast(dz) = \ast(dz - rb) + r \ast b = (b - r(dz - rb)) \wedge R^2 db = R^4 b \wedge db - rR^2 dz \wedge db. \quad (44)$$

The form  $\ast dz$  is closed since  $d \ast dz = R^4 db \wedge db = 0$ . We normalize  $\ast dz$  to obtain a calibrating form  $\frac{1}{R} \ast dz$ , whose restriction to the 3-sphere  $S^3 \subset S^1 \times S^3$  coincides with the volume form  $R^3 b \wedge db$  of this round sphere of radius  $R$ .

Now take two 3-spheres, denoted respectively  $(A, a)$  and  $(B, b)$ , with their contact forms  $a$  and  $b$ . Choose metrics on  $A$  and  $B$  as follows. The sphere  $A$  is endowed with the metric of a Riemannian submersion, whose fiber is of length  $2\pi$ , over a round 2-sphere of radius  $\sqrt{r}R$  (the reason for choosing  $\sqrt{r}R$  instead of  $R^{3/2}$  will become clear later). The sphere  $B$  is a round 3-sphere of radius  $R$ . We form the direct sum metric on  $A \times B$ , of volume growth on the order of  $R^6$  when  $R \rightarrow \infty$ . Next we modify it by adding the nondiagonal term

$$-2rab \text{ where } r = \sqrt{R^2 - 1}, \quad (45)$$

and  $a$  and  $b$  are the contact forms. The new metric on  $A \times B$  has volume growth  $R^5$  instead of  $R^6$ , due to the appearance in the determinant of the unimodular matrix

$$\begin{bmatrix} 1 & r \\ r & R^2 \end{bmatrix} \quad (46)$$

with respect to the pair of vectors dual to  $(a, b)$ . More precisely, let  $(a, a', a'')$  be a standard basis completing  $a$ , and similarly for  $b$ , as before. The metric described above can be written down as follows:

$$rR^2((a')^2 + (a'')^2) + (a - rb)^2 + b^2 + R^2((b')^2 + (b'')^2). \quad (47)$$

Here we inflate the metric of the contact plane of the first factor  $A$  to endow it with volume growth  $R^3$ , that of the second factor. If  $S^1 \subset A$  is

a Hopf fiber, the restriction of the metric to  $S^1 \times B \subset A \times B$  coincides with Gromov's metric. Then  $\text{sys}_3([A]) = \text{vol}(A) = 8\pi^2 r R^2$  by a standard argument using the coarea inequality. As far as  $B$  is concerned, we show that  $\text{sys}_3([B])$  has the growth of  $\text{vol}(B) = 2\pi^2 R^3$ . We show this by using a calibrating form described below.

By analogy with the case of  $S^1 \times S^3$ , one would like to replace  $*(dz)$  by  $*(a \wedge da)$ . The difficulty is that this form is no longer closed. There are two natural ways to introduce a corrective term, only one of which works, as we now show.

**Lemma D.6:** *With respect to the metric (47) we have:*

- (i)  $\|da\| = r^{-1}R^{-2}$  and  $\|db\| = R^{-2}$ ;
- (ii)  $\|a \wedge da\| = r^{-1}R^{-1}$ ;
- (iii)  $d*(a \wedge da) = -da \wedge db$ .

**Proof.** (i) Indeed,  $\|\sqrt{r}Ra'\| = 1$  and  $\|Rb'\| = 1$ . (ii) We have  $\|a \wedge da\| = \|a\|\|a'\|\|a''\| = \sqrt{1+r^2}r^{-1}R^{-2} = r^{-1}R^{-1}$ . (iii) We have

$$\begin{aligned} * (a \wedge da) &= *(((a - rb) + rb) \wedge da) = (b - r(a - rb))\|da\|\|db\|^{-1}db \\ &= r^{-1}((1+r^2)b - ra)db. \end{aligned}$$

Note that the restriction of the form  $rR*(a \wedge da)$  to a coordinate sphere  $B \subset A \times B$  is

$$R(1+r^2)b \wedge db = R^3 b \wedge db, \quad (49)$$

the volume form of  $B$  induced by the metric (47). We have  $d*(a \wedge da) = r^{-1}(R^2db - rda) \wedge db = -da \wedge db$ . Note that we chose the metric on  $A$  so as to render the formula for  $d*(a \wedge da)$  free of  $r$  and  $R$ . Thus we need to correct  $*(a \wedge da)$  by  $(1-t)da \wedge b + ta \wedge db$ , for some  $t \in \mathbb{R}$ , to make it closed.

Now  $\|a \wedge db\| = \|a\|\|b'\|\|b''\| = \sqrt{1+r^2}R^{-2} = R^{-1}$  while  $\|da \wedge b\| = \|a'\|\|a''\|\|b\| = r^{-1}R^{-2}$ , which is much smaller. In view of (ii) above, the closed form

$$r^2(* (a \wedge da) + da \wedge b) \quad (50)$$

is of norm which tends to 1 as  $r \rightarrow \infty$ . Using this form, we obtain volume estimates on the order of  $R^3$  for  $[B]$  and also any class  $\alpha[A] + \beta[B]$  with  $\beta$  in  $\mathbb{Z}^*$ . This completes the proof of Theorem D.3.

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# Glossary of Notation

$\ \alpha\ _{\text{alg}}$ , 3.20	$\text{Dir}_1$ , $3\frac{1}{2+}.37$
$\ \alpha\ _{\text{geo}}$ , 3.21	$\text{distort}(X)$ distortion, 1.14
$\ \alpha_{\mathbb{R}}\ $ , 4.19	$\text{ExDis}(X, \kappa, e)$ , $3\frac{1}{2+}.35$
$\ h\ _{\text{cell}}$ , 5.40	$\text{Exp}(X, \kappa, \rho)$ , $3\frac{1}{2+}.35$
$\ [V]_{\mathbb{Z}}\ _{\Delta}^M$ , $\ [V]_{\mathbb{R}}\ _{\Delta}^M$ , 5.38	$\text{Ex}(\lambda) = \text{Ex}_{P,Q,X}(\lambda)$ , $2.30\frac{1}{2+}$
$\square_{\lambda}$ , $3\frac{1}{2+}.2$	$\text{FilRad}(X)$ , 3.35
$\underline{\square}_{\lambda}$ , $3\frac{1}{2+}.2$	$h(\{\gamma_i\})$ , 5.11
$AvDi$ , $3\frac{1}{2+}.43$	$h(\Gamma)$ , 5.11
$\text{Cap}_{\varepsilon}(X)$ , 2.14	$h^k(X; \Gamma)$ , 5.33
$\text{codil}(f)$ , $1.25\frac{1}{2+}$	$\underline{H}_{\lambda} \mathcal{L}\iota_1$ $3\frac{1}{2+}.45$
$\text{codil}_x(f)$ , $1.25\frac{1}{2+}$	$K_r(X)$ , 3.27
$\text{CRad}(\nu; m - \kappa)$ , $3\frac{1}{2+}.31$	$\text{Ledi}(y_1, y_2)$ , $3\frac{1}{2+}.46$
$d_{\mathbf{H}}(X, Y)$ , 3.4	$\text{LeRad}(Z^n; -\kappa)$ , $3\frac{1}{2+}.46$
$d_{\mathbf{HL}}(X, Y)$ , 3.19	$\text{Lid}_b$ $3\frac{1}{2+}.9$
$d_{\mathbf{L}}(X, Y)$ , 3.1	$\mathcal{Lip}_s / \text{const}$ , $3\frac{1}{2+}.36$
$\delta\text{-Inv}(X/Y)$ , $3\frac{1}{2+}.48$	$M_r$ , $1.19_+$
$\deg(f)$ , 2.2	$\text{me}_{\lambda}$ , $3\frac{1}{2+}.4$
$\deg^*(f)$ , $2.8\frac{1}{2+}$	$\mu_r^X$ , $3\frac{1}{2+}.4$
$\text{di}_{\lambda}$ , $3\frac{1}{2+}.9$	$\text{ObsCRad}$ , $3\frac{1}{2+}.31$
$\text{dil}(f)$ dilatation of $f$ , 1.1	$\text{ObsDiam}_Y(X)$ , $3\frac{1}{2+}.20$
$\text{dil}_x(f)$ local dilatation, 1.1	

$\text{ObsInv}_Y(X, -\kappa)$ , 3<sub>2+</sub><sup>1</sup>.F

$\mathcal{P}$ , 3<sub>2+</sub><sup>1</sup>.51

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$\text{Tra}_\lambda$ , 3<sub>2+</sub><sup>1</sup>.10

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$\text{vol}(f)$ , 2.7

$|\text{vol}|(f)$ , 2.8<sub>2+</sub><sup>1</sup>

$\text{vol}^{(r)}$ , 3.34<sub>2+</sub><sup>1</sup>

$\mathcal{X}$ , 3<sub>2+</sub><sup>1</sup>.D

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