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QUANTUM ERROR CORRECTING CODES AND 4-DIMENSIONAL ARITHMETIC HYPERBOLIC MANIFOLDS

LARRY GUTH AND ALEXANDER LUBOTZKY

ABSTRACT. Using 4-dimensional arithmetic hyperbolic manifolds, we construct some new homological quantum error correcting codes. They are LDPC codes with linear rate and distance n^ϵ . Their rate is evaluated via Euler characteristic arguments and their distance using \mathbb{Z}_2 -systolic geometry. This construction answers a question of Zémor [Z], who asked whether homological codes with such parameters could exist at all.

1. INTRODUCTION

The goal of this paper is to present homological quantum error correcting codes (QECC) based on a family of finite sheeted congruence covers of a fixed 4-dimensional arithmetic hyperbolic manifold. We then estimate the rate and distance of these codes and show that they answer a question of Zémir [Z], who asked if homological codes with such parameters could exist at all.

A (classical linear) code is a subspace C of \mathbb{Z}_2^n of dimension k . Its rate r is, by definition, $r = \frac{k}{n}$ and its distance is defined as $d = d(C) = \min\{wt(\alpha) \mid 0 \neq \alpha \in C\}$ where $wt(\alpha)$ is the Hamming weight of α , i.e., the number of non-zero entries of α . Write $\delta = \delta(C)$ for $\frac{d}{n}$ - the normalized distance. The standard terminology is that C is an $[n, k, d]$ -code.

The quantum codes we will consider here will all be the so called CSS-codes (see [NC], [P], [F1] for an explanation what the following construction has to do with quantum error correction). A quantum CSS-code $\mathcal{C} = (W_1, W_2)$ is defined by two orthogonal subspaces W_1 and W_2 in \mathbb{Z}_2^n , i.e., for every $\alpha = (a_1, \dots, a_n) \in W_1$ and $\beta = (b_1, \dots, b_n) \in W_2$, $\alpha \cdot \beta = 0$ where $\alpha \cdot \beta := \sum_{i=1}^n a_i b_i$. Let W_1^\perp, W_2^\perp be the orthogonal subspaces to W_1 and W_2 , so: $W_1 \subseteq W_2^\perp$ and $W_2 \subseteq W_1^\perp$. The dimension k of \mathcal{C} is defined as $k = \dim(W_1^\perp/W_2) = \dim(W_2^\perp/W_1) = n - \dim W_1 -$

$\dim W_2$ and the rate $r = \frac{k}{n}$. The distance of the code \mathcal{C} is defined as:

$$d(W_1, W_2) = \min\{wt(\alpha) \mid \alpha \in (W_1^\perp \setminus W_2) \cup (W_2^\perp \setminus W_1)\}$$

and $\delta = \delta(\mathcal{C}) = \frac{d}{n}$. Here one writes that \mathcal{C} is an $[[n, d, c]]$ -code.

While studying codes, one is usually interested in a family of codes when $n \rightarrow \infty$. By abuse of the language we say that C (resp. \mathcal{C}) is a good code if r and δ are both bounded away from 0, or equivalently, the dimension and the distance grow linearly with the length n of the code.

The code C (resp. \mathcal{C}) is called LDPC (= low density parity check) if C^\perp is spanned by vectors of bounded Hamming weight (resp. $W_i = (W_i^\perp)^\perp$ is spanned by vectors of bounded weight for $i = 1$ and 2).

Good LDPC classical codes have been known to exist, by random consideration, since the fundamental work of Gallager [Ga] in the 60's. In 1996, Sipser and Spielman made an explicit construction of such codes using expander graphs ([SS]). It is still an open problem if good LDPC quantum codes exist at all.

Manifolds and simplicial complexes offer a natural construction of quantum LDPC codes, the so called "homological codes", in the following way:

Let X be a finite simplicial complex of dimension D (if M is a manifold, one can replace M by a triangulation X of it), i.e., X is a set of subsets of $X^{(0)}$ (the set of vertices of X) of size $\leq D + 1$ with the property that if $F \in X$ and $G \subseteq F$ then $G \in X$. Let $X^{(i)}$ be the set of subsets in X of size $i + 1$. The space of mod 2 i -chains, $C_i = C_i(X, \mathbb{Z}_2)$, is the \mathbb{Z}_2 -vector space spanned by $X^{(i)}$. The space of mod 2 i -cochains, $C^i = C^i(X, \mathbb{Z}_2)$, is the space of functions from $X^{(i)}$ to \mathbb{Z}_2 . It is convenient to identify C_i and C^i in the clear way.

Let $\partial_i : C_i \rightarrow C_{i-1}$ be the boundary map, i.e.,

$$\partial_i(F) = \sum_{\substack{G \subset F \\ |G|=i}} G \text{ for } F \in X^{(i)}$$

and its adjoint $\delta_i : C_i \rightarrow C_{i+1}$ the cobounding map

$$\delta_i(F) = \sum_{\substack{F \subset G \\ |G|=i+2}} G$$

(recall that as we work in characteristic two, we can ignore the orientation). It is well known and easy to prove that for all i

$$(1) \quad \partial_i \circ \partial_{i+1} = 0 \text{ and } \delta_i \circ \delta_{i-1} = 0.$$

Hence $B_i :=$ the i -boundaries $= \text{Im}\partial_{i+1}$ (resp: $B^i =$ the i -coboundaries $= \text{Im}\delta_{i-1}$) is contained in $Z_i =$ the i -cycles $= \text{Ker}\partial_i$ (resp: $Z^i =$ the i -cocycles $= \text{Ker}\delta_i$).

Moreover, one can easily check that (1) implies the following (which is crucial for the quantum codes application):

$$(2) \quad B_i^\perp = Z^i \quad \text{and} \quad (B^i)^\perp = Z_i.$$

One can therefore associate with X , for every $i \leq D$, a quantum CSS-code $\mathcal{C} = (B_i, B^i)$ whose length is $n = |X^{(i)}|$, and its dimension is $k = \dim Z_i/B_i = \dim H_i(X, \mathbb{Z}_2)$, i.e., the dimension of the homology of X (or of M) with coefficients in \mathbb{Z}_2 . The latter is also $k = \dim Z^i/B^i = \dim H^i(X, \mathbb{Z}_2)$, i.e., the dimension of the i -cohomology group. Finally, the distance $d = d(\mathcal{C})$ is the Hamming weight of a non-trivial homology or cohomology class i.e., the minimum weight of an i -cycle (which is not an i -boundary) or i -cocycle (which is not an i -coboundary).

Homological codes are attractive as if one let M varies over finite sheeted covers of a fixed compact manifold, then the codes obtained are automatically LDPC since B_i (resp. B^i) is generated by the images of the cells of dimension $i+1$ (resp. $i-1$). This gives these codes great potential, and this is what brings us to systolic geometry.

Systolic geometry is a subarea of Riemannian geometry studying volumes of non-trivial cycles and cocycles. Fairly recently, it has been noticed that there is a connection between quantum error correcting codes and systolic geometry with \mathbb{Z}_2 coefficients (cf. [Fr], [MFL], [Z], [F2]).

Some of the most studied quantum codes, e.g. the toric codes and surface codes (cf. [Z] and [F1]), can be considered as special cases of homological codes. But, while they are LDPC they are all far from being good.

Zémor [Z], based on the known examples and on intuition coming from graph theory, made the following suggestion:

Question (Zémor [Z]). Let \mathcal{C} be an $[[n, k, d]]$ homological quantum code. Is it always true that $kd^2 \leq n^{1+o(1)}$? (or, in the notation of $r = \frac{k}{n}$ and $\delta = \frac{d}{n}$, $r\delta^2 \leq n^{-2+o(1)}$)

In [F2], Fetaya essentially proved that this is indeed true for codes coming from 2-dimensional surfaces. We prove that it is not the case for codes coming from 4-dimensional manifolds.

Theorem 1. *There exist $\varepsilon, \varepsilon', \varepsilon'' > 0$ and a sequence of 4-dimensional hyperbolic manifolds M with triangulations X such that the associated*

homological quantum codes constructed in $C^2(X, \mathbb{Z}_2) = C_2(X, \mathbb{Z}_2)$ are $[[n, \varepsilon'n, n^{\varepsilon''}]]$ codes and so:

$$kd^2 \geq n^{1+\varepsilon}.$$

Theorem 1 will be deduced from the following geometric result.

Theorem 2. *There is a constant $\epsilon > 0$, a closed hyperbolic 4-manifold M_0 and a sequence of finite sheeted covers $M_j \rightarrow M_0$ with $\text{Vol}_4 M_j \rightarrow \infty$ obeying the following estimates:*

1. *The dimension of $H_2(M_j, \mathbb{Z}_2)$ is $\geq (1/100) \text{Vol}_4 M_j$.*
2. *Every homologically non-trivial mod 2 2-cycle in M_j has area $\geq (\text{Vol}_4 M_j)^\epsilon$.*

A crucial ingredient in the proof is a theorem of Anderson [A] which says that every homologically non-trivial i -cycle in a D -dimensional hyperbolic manifold has volume at least the volume of a hyperbolic i -ball of radius R , where R is the injectivity radius of the manifold. Note that when $i = 1$, this gives a linear bound on the volume, while for $i > 1$ it gives an exponential bound. So we get much better lower bounds when $i > 1$. For homological quantum codes, one needs lower bounds on both i -cycles and i -cocycles. By Poincaré duality (see Section 2), one wants lower bounds on i -cycles and $(D - i)$ -cycles. That is why we chose to work with $D = 4$ and $i = 2$, which is the smallest dimension where i and $D - i$ are more than 1.

We should note however that the existence of LDPC quantum codes with parameters $[[n, \varepsilon'n, n^{\varepsilon''}]]$ is not new. In [TZ], Tillich and Zémor discovered such codes with parameters $[[n, \varepsilon'n, n^{0.5}]]$. In fact, for the codes we construct, $\varepsilon'' \leq 0.3$ - see Remark 20. The point of the current work is that our codes are homological. This brings back the systolic geometry to the race of finding good LDPC quantum codes, if such codes really exist.

The paper is organized as follows. In Section 2, we describe the connection between distance of codes and systoles. We deduce Theorem 1 from Theorem 2, postponing the proof of Theorem 2 to the next two sections. In Section 3, we estimate the dimension of the homology groups using Euler characteristic arguments. In Section 4, we estimate the sizes of cycles in congruence covers. Along the way, we give lower bounds on the injectivity radius of the congruence covers. This section is making a crucial use of results of Anderson [A] in hyperbolic geometry. As we expect this paper to have a diverse audience, we tried whenever we can to elaborate a bit on some methods even when they

are well known to experts. In particular, in Section 5 we explain the basic idea behind Anderson's theorem.

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2. CODES AND SYSTOLES

Suppose that (M^n, g) is a closed Riemannian manifold equipped with a triangulation X . In the introduction, we recalled the *CSS* code corresponding to i -dimensional chains in X : this is the code (B_i, B^i) . We would like to understand how the distance of this code is related to the geometry of (M, g) .

The i -dimensional systole of (M^n, g) with coefficients in \mathbb{Z}_2 is the infimal volume of a homologically non-trivial Lipschitz i -cycle in (M^n, g) . We denote it by $Sys_i(M^n, g)$. Below, we will briefly recall what these words mean. The systole is a quantity from Riemannian geometry which is analogous to the distance of a code. In particular, we recall the following result connecting systoles and codes.

Proposition 3. *Suppose that M_0^D is a closed D -dimensional manifold equipped with a Riemannian metric g_0 and a triangulation X_0 . Let $M \rightarrow M_0$ be a finite sheeted cover, and let g and X be the pullbacks of g_0 and X_0 . Then the distance of the code $(B_i(X), B^i(X))$ obeys the inequality*

$$(3) \quad d(B_i(X), B^i(X)) \geq c(M_0, g_0, X_0) \min(Sys_i(M, g), Sys_{D-i}(M, g)),$$

where $c(M_0, g_0, X_0)$ is a constant.

Let us now recall Lipschitz chains and cycles, to clarify the definition of the systole. A Lipschitz i -chain with coefficients in \mathbb{Z}_2 is a finite sum $\sum_j a_j f_j$ where $a_j \in \mathbb{Z}_2$ and f_j is a Lipschitz map from the standard i -simplex Δ^i to M . A Lipschitz 1-chain is a bunch of parametrized curves in M , and a Lipschitz i -chain is a bunch of parametrized i -simplices. We denote the Lipschitz i -chains by $C_{i,Lip}(M, \mathbb{Z}_2)$. There is a boundary map $\partial_{i,Lip} : C_{i,Lip}(M, \mathbb{Z}_2) \rightarrow C_{i-1,Lip}(M, \mathbb{Z}_2)$, defined by restricting each map f_j to the $(i-1)$ -simplices in the boundary of Δ^i . The Lipschitz i -cycles form the kernel of $\partial_{i,Lip}$. Each i -cycle in $Z_i(X, \mathbb{Z}_2)$ can be considered as a Lipschitz cycle, but most Lipschitz cycles in (M^n, g) do not come from any element of $Z_i(X, \mathbb{Z}_2)$. The reader can visualize the i -cycles of $Z_i(X, \mathbb{Z}_2)$ as surfaces made from

the i -faces of X , whereas Lipschitz i -cycles do not have to lie in the i -skeleton of X .

A standard result of topology says that the homology of the chain complex of Lipschitz chains is the same as the homology $H_i(X, \mathbb{Z}_2)$. In particular, an i -cycle in $Z_i(X, \mathbb{Z}_2)$ is homologically non-trivial if and only if the corresponding Lipschitz cycle is homologically non-trivial.

The volume of a Lipschitz map $f_j : \Delta^i \rightarrow (M, g)$, is defined to be the volume of the pullback metric $f_j^*(g)$ on Δ^i . We can also think of it as the i -dimensional volume of $f_j(\Delta^i)$, counted with multiplicity if the image covers some i -dimensional surface multiple times. The volume of the Lipschitz chain $\sum_j a_j f_j$ is $\sum_j |a_j| \text{Vol}_i f_j$.

Now suppose that α is a chain in $C_i(X, \mathbb{Z}_2)$. Since we are working with mod 2 coefficients, we can abuse notation and think of α as a subset of the i -dimensional faces of X . The weight of α is just the number of i -faces in α . The volume of the Lipschitz chain corresponding to α is the sum of the volumes of the i -faces in α .

Therefore, we get the following inequalities between the weight of $\alpha \in Z_i(X, \mathbb{Z}_2)$ and the volume of α as a Lipschitz cycle.

$$(\min_{F \subset X} \text{Vol}_i F) wt(\alpha) \leq \text{Vol} \alpha \leq (\max_{F \subset X} \text{Vol}_i F) wt(\alpha).$$

In these formulas, the maximum or minimum is over all the i -faces of X .

In Proposition 3, we start with a closed manifold (M_0, g_0) with a triangulation X_0 . Then we consider finite sheeted covers $M \rightarrow M_0$ with pullback metric g and pullback triangulation X . The maximum and minimum volumes of i -faces in X are the same as in X_0 , so they are uniformly bounded. Therefore, the volume and weight of α agree up to a constant factor. These observations prove the following lemma.

Lemma 4. *Suppose that $M \rightarrow M_0$ is a finite sheeted cover. Suppose that M_0 is equipped with a metric g_0 and a triangulation X_0 , and let g and X be the pullbacks. Then for any $\alpha \in Z_i(X, \mathbb{Z}_2)$, we have*

$$wt(\alpha) \geq c_1(M_0, g_0, X_0) \text{Vol}_i \alpha.$$

As a corollary, we can bound the minimal weight of a homologically non-trivial cycle α in terms of the systole of (M_i, g_i) .

Lemma 5. *Suppose that $M \rightarrow M_0$ is a finite sheeted cover. Suppose that M_0 is equipped with a metric g_0 and a triangulation X_0 , and let g*

and X be the pullbacks. Then the minimal weight of any α in $Z_i \setminus B_i$ is at least $c_2(M_0, g_0, X_0) Sys_i(M, g)$.

This lemma is the first half of the proof of Proposition 3. To finish the proof, we have to give a lower bound for the weights of α in $Z^i \setminus B^i$. We can do this using Poincaré duality for the manifold M .

Suppose that M^D is a closed D -dimensional manifold with triangulation X . Then there is a Poincaré dual polyhedral structure X' on M . There is a vertex of X' in the center of each D -simplex of X . There is an edge of X' through the center of each $(D - 1)$ -face of X . The $(D - 1)$ -face borders exactly two D -faces, and the edge goes from the center of one to the center of the other. More generally, there is an i -face of X' through the center of each $(D - i)$ -simplex in X . (For a description of dual polyhedral structures and Poincaré duality, see Chapter 5.2 of [Sha].)

Since each i -dimensional face of X corresponds to a unique $(D - i)$ -dimensional face of X' , we get a Poincaré duality isomorphism $P : C^i(X, \mathbb{Z}_2) \rightarrow C_{D-i}(X', \mathbb{Z}_2)$. The key feature of Poincaré duality is that the coboundary map on cochains in X corresponds to the boundary map on chains in X' . In formulas, this means that for each $\alpha \in C^i(X, \mathbb{Z}_2)$,

$$P(\delta_i \alpha) = \partial_{D-i}(P\alpha).$$

In particular, Poincaré duality maps cocycles in X to cycles in X' and coboundaries in X to boundaries in X' . Therefore, the minimum weight of any $\alpha \in Z^i(X, \mathbb{Z}_2) \setminus B^i(X, \mathbb{Z}_2)$ is the same as the minimal weight of any α in $Z_{D-i}(X', \mathbb{Z}_2) \setminus B_{D-i}(X', \mathbb{Z}_2)$. Therefore, we get the following inequalities between the weight of $\alpha \in Z^i(X, \mathbb{Z}_2)$ and the volume of $P\alpha$ as a Lipschitz cycle:

$$\left(\min_{F \subset X'} \text{Vol}_{D-i} F \right) wt(\alpha) \leq \text{Vol}_{D-i} P\alpha \leq \left(\max_{F \subset X'} \text{Vol}_{D-i} F \right) wt(\alpha).$$

In these formulas, the maximum or minimum is over all the $(D - i)$ -faces of X' .

Now suppose again that M is a finite sheeted cover of a closed manifold M_0 , where M_0 is equipped with metric g_0 and triangulation X_0 . We let X'_0 be the Poincaré dual polyhedral structure for X_0 . We let g be the pullback of g_0 , X be the pullback of X_0 , and X' be the pullback of X'_0 . Now X' is still Poincaré dual to X . Moreover, the maximum and minimum volumes of faces in X' are the same as in X'_0 .

Therefore, we see that the weight of any $\alpha \in C^i(X, \mathbb{Z}_2)$ is at least $c(M_0, g_0, X_0, X'_0) \text{Vol}_{D-i} P\alpha$. Next suppose that $\alpha \in Z^i(X, \mathbb{Z}_2) \setminus B^i(X, \mathbb{Z}_2)$. Since Poincaré duality respects boundaries, it follows that $P\alpha \in Z_i(X', \mathbb{Z}_2) \setminus B_i(X', \mathbb{Z}_2)$. Therefore, the minimal weight of any $\alpha \in Z^i(X, \mathbb{Z}_2) \setminus B^i(X, \mathbb{Z}_2)$ is at least $c(M_0, g_0, X_0, X'_0) \text{Sys}_{D-i}(M, g)$.

This finishes the proof of Proposition 3. Proposition 3 is a bridge connecting geometric properties of Riemannian manifolds and codes. Using this bridge, we can build interesting codes from interesting towers of Riemannian manifolds. In particular we will prove the following result about congruence covers of hyperbolic 4-manifolds.

Theorem 6. *There is a constant $\epsilon > 0$, a closed hyperbolic 4-manifold M_0 and a sequence of finite sheeted covers $M_j \rightarrow M_0$ with $\text{Vol}_4 M_j \rightarrow \infty$ obeying the following estimates.*

1. *The dimension of $H_2(M_j, \mathbb{Z}_2)$ is $\geq (1/100) \text{Vol}_4 M_j$.*
2. *$\text{Sys}_2(M_j) \geq (\text{Vol}_4 M_j)^\epsilon$. In other words, every homologically non-trivial mod 2 2-cycle in M_j has area $\geq (\text{Vol}_4 M_j)^\epsilon$.*

(We use the hyperbolic metric on each M_j pulled back from M_0 .)

Using this theorem, we can quickly construct codes proving Theorem 1. We fix a triangulation X_0 of M_0 . We let X_j be the pullback triangulation of M_j . Then we consider the quantum code $(B_2(X_j, \mathbb{Z}_2), B^2(X_j, \mathbb{Z}_2))$.

In this code, the spaces B_2, B^2 are subspaces of $C_2(X_j, \mathbb{Z}_2)$. This is a vector space whose dimension n is equal to the number of 2-faces in X_j . We let D_j be the degree of the cover $M_j \rightarrow M_0$. The number of 2-faces in X_j is D_j times the number of 2-faces in X_0 . Up to a factor $C(M_0, X_0)$, n is equal to D_j . Also, up to a constant factor, D_j is equal to $\text{Vol}_4 M_j$. So $n \leq c_1 \text{Vol}_4 M_j$.

The dimension of the code is $k = \text{Dim } H_2(X_j, \mathbb{Z}_2) = \text{Dim } H_2(M_j, \mathbb{Z}_2) \geq 1/100 \text{Vol}_4 M_j$. Therefore, $k \geq c_2 n$. In other words, these codes have a linear rate.

Finally, Proposition 3 implies that the distance of the code is at least $c_3 \text{Sys}_2(M_j) \geq c_4 n^\epsilon$.

We will prove Theorem 6 in the next sections using hyperbolic geometry.

3. EULER CHARACTERISTIC OF HYPERBOLIC MANIFOLDS

The Euler characteristic of a hyperbolic manifold can be computed by the Gauss-Bonnet-Chern theorem.

Theorem 7. (Allendoerfer-Weil, Chern [C]) *If M^{2n} is a closed oriented manifold with Riemannian metric g , then the Euler characteristic of M is given by $c_n \int_M Pf(K_g) dvol_g$, where $c_n > 0$ is a dimensional constant, and $Pf(K_g)$ is the Pfaffian of the curvature of g .*

For a hyperbolic $2n$ -manifold, $Pf(K_{hyp})$ is a constant, and we see that the Euler characteristic of (M^{2n}, hyp) is $c'_n Vol_{2n}(M, hyp)$, for some constant c'_n . We will evaluate this constant, and we will see that it is never zero, and that the sign of c'_n is $(-1)^n$.

Corollary 8. *If M^{2n} is a closed oriented hyperbolic manifold, then the Euler characteristic of M is $(-1)^n \cdot 2 Vol M / Vol S^{2n}$.*

Proof. For the unit sphere, the Gauss-Bonnet-Chern theorem gives $2 = c_n Pf(K_{S^{2n}}) Vol S^{2n}$. Therefore, $c_n Pf(K_{S^{2n}}) = 2 / Vol S^{2n}$. The curvature of hyperbolic space is negative the curvature of the unit sphere: $K_{H^{2n}} = -K_{S^{2n}}$. From the formula for the Pfaffian in [C], it follows that $Pf(K_{H^{2n}}) = (-1)^n Pf(K_{S^{2n}})$. For (M^{2n}, hyp) , the Gauss-Bonnet-Chern theorem implies that the Euler characteristic is $c_n Pf(K_{H^{2n}}) Vol(M, hyp) = (-1)^n 2 (Vol S^{2n})^{-1} Vol(M, hyp)$. \square

As a corollary, we see that for a hyperbolic 4-manifold M , the dimension of $H_2(M, \mathbb{Z}_2)$ grows linearly with the volume of M .

Corollary 9. *Suppose that M is a connected closed hyperbolic 4-manifold with volume V . Then $\text{Dim } H_2(M, \mathbb{Z}_2)$ is at least $(2 / Vol S^4)V - 2$.*

Proof. By the Corollary above, the Euler characteristic of M is $(2 / Vol S^4)V$. The Euler characteristic of M is equal to $\sum_{d=0}^4 (-1)^d \text{Dim } H_d(M, \mathbb{Z}_2)$. Since M is connected, $H_0(M_i)$ and $H_4(M_i)$ have dimension 1. Since the odd dimensions contribute negatively, we get $\text{Dim } H_2(M_i) \geq (2 / Vol S^4)V - 2$. \square

For all V sufficiently large, we see that $\text{Dim } H_2(M, \mathbb{Z}_2) \geq (1/100)V$. This proves the lower bound on the dimension of H_2 in Theorem 6.

4. CONGRUENCE COVERS OF HYPERBOLIC MANIFOLDS

Recall that the group of orientation-preserving isometries of hyperbolic space \mathbb{H}^D is the connected component of the identity of $SO(D, 1)$, which we denote $SO^o(D, 1)$. We will make closed hyperbolic manifolds by quotienting \mathbb{H}^D by discrete subgroups of $SO^o(D, 1)$. The discrete

subgroups we use will be arithmetic lattices. We define arithmetic lattices below, but let us begin with a couple of examples.

The simplest example is $SO(D, 1, \mathbb{Z}) \subset SO(D, 1, \mathbb{R})$. Here we define $SO(D, 1, \mathbb{R}) \subset GL(D + 1, \mathbb{R})$ as the group of matrices that preserve the quadratic form $-x_0^2 + x_1^2 + \dots + x_D^2$ on \mathbb{R}^{D+1} , and $SO(D, 1, \mathbb{Z})$ as the subgroup of matrices that have integer entries. It turns out that the quotient $SO(D, 1, \mathbb{Z}) \backslash \mathbb{H}^D$ has finite volume but is not compact (cf. Chapter 6 of [Mo]). Since we will use closed hyperbolic manifolds, we need a trickier example.

Let f be the quadratic form $-\sqrt{2}x_0^2 + \sum_{i=1}^D x_i^2$. Let $SO_f \subset GL(D + 1, \mathbb{R})$ be the subgroup of matrices that preserve f and have determinant 1. The form f has signature $(D, 1)$ and so SO_f is conjugate to $SO(D, 1)$ in $GL(D + 1, \mathbb{R})$. We fix an isomorphism $SO_f \rightarrow SO(D, 1)$ and so we think of the component of the identity, $SO^o(f)$, as the group of orientation-preserving isometries of \mathbb{H}^D .

Now we let $SO_f(\mathbb{Z}[\sqrt{2}]) \subset SO_f$ be the subgroup of matrices with entries in $\mathbb{Z}[\sqrt{2}]$. The group $SO_f(\mathbb{Z}[\sqrt{2}])$ is a discrete cocompact subgroup of SO_f . It is not obvious that $SO_f(\mathbb{Z}[\sqrt{2}])$ is either discrete or cocompact. There is a short elegant proof that it is discrete, which we include. For a proof that it is cocompact, see Chapter 6 of [Mo].

The ring $\mathbb{Z}[\sqrt{2}] \subset \mathbb{R}$ is not discrete. There are two group homomorphisms from $\mathbb{Z}[\sqrt{2}]$ to \mathbb{R} . One sends $\sqrt{2}$ to $\sqrt{2}$, the other sends $\sqrt{2}$ to $-\sqrt{2}$. Let ϕ_1, ϕ_2 be the two homomorphisms, where $\phi_1(\sqrt{2}) = \sqrt{2}$ and $\phi_2(\sqrt{2}) = -\sqrt{2}$. Now the image $(\phi_1, \phi_2)\mathbb{Z}[\sqrt{2}] \subset \mathbb{R}^2$ is discrete.

If we apply the map ϕ_2 to each coefficient of a matrix $m \in SO_f(\mathbb{Z}[\sqrt{2}])$, we do not get an element of SO_f . Instead we get an element of $SO_{\tilde{f}}$ where \tilde{f} is the quadratic form $+\sqrt{2}x_0^2 + \sum_{i=1}^D x_i^2$. So ϕ_2 induces a group homomorphism $\phi_2 : SO_f(\mathbb{Z}[\sqrt{2}]) \rightarrow SO_{\tilde{f}}$. Combining ϕ_1 and ϕ_2 , we get an injective homomorphism $SO_f(\mathbb{Z}[\sqrt{2}]) \rightarrow SO_f \times SO_{\tilde{f}}$. The image of this homomorphism is discrete. Moreover, \tilde{f} has signature $(D + 1, 0)$, and so $SO_{\tilde{f}}$ is conjugate to $SO(D + 1)$ and is compact. Therefore, $SO_f(\mathbb{Z}[\sqrt{2}])$ is a discrete subgroup of SO_f .

We let $\Gamma_1 = SO_f(\mathbb{Z}[\sqrt{2}]) \subset SO_f$, and we think of $SO(f)$ acting on hyperbolic space. Next we define subgroups $\Gamma_N \subset \Gamma_1$ as follows. A matrix in $SO_f(\mathbb{Z}[\sqrt{2}])$ can be written (uniquely) in the form $A + B\sqrt{2}$, where A, B are matrices with integer coefficients. Such a matrix lies in Γ_N if and only if $A = Id$ modulo N and $B = 0$ modulo N . The subgroups Γ_N are called principal congruence subgroups of Γ_1 . The

groups Γ_N is a normal subgroup of Γ_1 , because it is the kernel of the reduction mod N map from $SO_f(\mathbb{Z}[\sqrt{2}])$ to $SO_f((\mathbb{Z}/N\mathbb{Z})[\sqrt{2}])$.

For all sufficiently large N , Γ_N acts without fixed points on \mathbb{H}^D , which we will prove below. Therefore, we can define the hyperbolic manifolds $M_N = \Gamma_N \backslash \mathbb{H}^D$ for all sufficiently large N . Taking $D = 4$, these hyperbolic manifolds are the examples in Theorem 6.

The index of Γ_N in Γ_1 is equal to the cardinality of the image of $SO_f(\mathbb{Z}[\sqrt{2}])$ in $SO_f((\mathbb{Z}/N\mathbb{Z})[\sqrt{2}])$. This cardinality is at most the cardinality of the set of $(D + 1) \times (D + 1)$ matrices with coefficients in the ring $(\mathbb{Z}/N\mathbb{Z})[\sqrt{2}]$, and so it is at most $N^{2(D+1)^2}$. A more accurate estimate is $N^{2 \dim SO_f}$, but we do not need it.

4.1. Injectivity radius estimates. Let M be a closed hyperbolic D -manifold. The injectivity radius of M is at least R if and only if, for every point $p \in M$, the metric ball around p with radius R is isometric to the hyperbolic D -ball of radius R . Next we need a lower bound for the injectivity radius of our hyperbolic manifolds $M_N = \Gamma_N \backslash \mathbb{H}^D$. Similar estimates have appeared before in some particular cases in [BS] and [KSV], and more generally in Section 3.C.6 of [Gr]). Let us prove it now directly for our concrete examples. Later we give a very general estimate.

Proposition 10. *Let D, Γ_1, Γ_N be as above. Then there are constants $c_1, c_2 > 0$ so that the injectivity radius of M_N is at least $c_1 \log N - c_2$.*

Since the volume of M_N grows like the index of Γ_N in Γ_1 , which grows polynomially in N we get the following corollary.

Corollary 11. *Let D, Γ_1, Γ_N be as above. Then there is a constant $c > 0$ so that the injectivity radius of M_N is at least $c \log \text{Vol } M_N$ for all N sufficiently large.*

Proof. Let $\pi : \mathbb{H}^D \rightarrow M_N = \Gamma_N \backslash \mathbb{H}^D$ be the quotient map. Let R be the injectivity radius of M_N . Since the injectivity radius of M_N is less than $2R$, there is some $p \in M$ so that the ball of radius $2R$ around p is not isometric to a ball of radius $2R$ in \mathbb{H}^D . Let p' be a preimage of p in \mathbb{H}^D . Let $B_{\mathbb{H}^D}(p', 2R)$ denote the ball around p' of radius $2R$ in \mathbb{H}^D . The map $\pi : B_{\mathbb{H}^D}(p', 2R) \rightarrow B_M(p, 2R)$ must not be an isometry. The only way it can fail to be an isometry is that two points of $B_{\mathbb{H}^D}(p', 2R)$ lie in the same Γ_N orbit. The distance between these two points must be $< 4R$. Therefore, there exists a non-identity element $n \in \Gamma_N$ and a point $x \in \mathbb{H}^D$ so that $d(x, nx) < 4R$. (Here d denotes the distance in \mathbb{H}^D .)

Let F be a fundamental domain for Γ_1 . Using the symmetries of the situation, we will show that we can arrange for the point x above to lie in F . There exists some $\gamma \in \Gamma_1$ so that $\gamma x \in F$. Since γ acts by isometries, we have

$$d(x, nx) = d(\gamma x, \gamma(nx)) = d(\gamma x, (\gamma n \gamma^{-1})(\gamma x)).$$

Now we define $x' = \gamma x \in F$ and $n' = \gamma n \gamma^{-1} \in \Gamma_N$, and we see that $d(x', n'x') < 4R$. (Here we used that Γ_N is normal.)

Next we use the fact that Γ_1 is cocompact. This implies that the fundamental domain has finite diameter $\text{Diam}(F)$. We fix a point $x_0 \in F$, and we are guaranteed that $d(x_0, x') \leq \text{Diam}(F)$. Since n' acts isometrically, $d(n'x_0, n'x') \leq \text{Diam}(F)$ as well. By the triangle inequality we get a bound on $d(x_0, n'x_0)$:

$$d(x_0, n'x_0) \leq 4R + 2 \text{Diam}(F). \quad (1)$$

Everything we said so far makes sense for any fundamental domain. It is convenient to choose a particular fundamental domain. We fix a point x_0 , and we consider the Dirichlet fundamental domain defined by

$$F := \{x \in \mathbb{H}^D \mid d(x, x_0) \leq d(\gamma x, x_0) \text{ for all } 1 \neq \gamma \in \Gamma_1\}.$$

Clearly $x_0 \in F$. Since Γ_1 is cocompact, F is compact. The boundary of F is defined to be the set of points $x \in F$ so that $d(x, x_0) = d(\gamma x, x_0)$ for some $1 \neq \gamma \in \Gamma_1$. We consider the translates γF for $\gamma \in \Gamma_1$. Two such translates can intersect only at points in the boundary. We say that $\gamma_1 F$ and $\gamma_2 F$ are adjacent if they intersect.

We can now prove that Γ_1 is finitely generated and describe a set of generators. We let $S \subset \Gamma_1$ be the set of $\gamma \in \Gamma_1$ so that $\gamma F \cap F$ is non-empty. Since Γ_1 acts properly discontinuously, there are only finitely many points of $\Gamma_1 x_0$ in any ball in \mathbb{H}^D . Since F is compact, we see that any compact set intersects only finitely many cells γF . In particular, it follows that S is finite. Also, $\gamma F \cap F = \gamma(F \cap \gamma^{-1}F)$, and so $\gamma \in S$ if and only if $\gamma^{-1} \in S$. Let s_1, s_2, \dots, s_T be the elements of S .

The set S generates Γ_1 . Indeed, let $\gamma \in \Gamma_1$. Consider a path from x_0 to γx_0 . This path is compact, so it intersects only finitely many cells γF . Using the path, we can choose a finite sequence of cells $F, \gamma_1 F, \gamma_2 F, \dots$, where consecutive cells are adjacent and the last cell is γF . By the definition of S , γ is a finite product $s_{i_1} \circ \dots \circ s_{i_w}$, with $s_{i_j} \in S$.

Recall that for each $\gamma \in \Gamma_1$, the word length $w_S(\gamma)$ is the shortest length of a product $s_{i_1} \circ \dots \circ s_{i_w}$ which is equal to γ , with the $s_i \in S$. We showed above that $w_S(\gamma) < \infty$ for any $\gamma \in \Gamma_1$. By making the argument more quantitative, we can give an upper bound for $w_S(\gamma)$ in terms of $d(x_0, \gamma x_0)$.

Lemma 12. *Let Γ_1, S be as above. For any $\gamma \in \Gamma_1$, $w_S(\gamma) \leq c_1(d(x_0, \gamma x_0) + 1)$.*

Proof. Since Γ_1 acts properly discontinuously, any unit ball contains a finite number of points of $\Gamma_1 x_0$. Since F is compact, any unit ball intersects a finite number of cells γF , $\gamma \in \Gamma_1$. Now since Γ_1 is cocompact, this upper bound is uniform over all unit balls. So we may assume that each unit ball in \mathbb{H}^D intersects at most c_1 cells γF .

Now take a path from x_0 to γx_0 of length $d(x_0, \gamma x_0)$. Divide this path into $d(x_0, \gamma x_0) + 1$ segments of length at most 1. Each of these segments intersects at most c_1 cells γF . So we can make a sequence of adjacent cells from F to γF using at most $c_1(d(x_0, \gamma x_0) + 1)$ cells. By the definition of S , we see that $w_S(\gamma) \leq c_1(d(x_0, \gamma x_0) + 1)$. \square

This lemma is all that we will use in the proof of the injectivity radius estimate, but for context it is useful to be aware of the following more general result.

Lemma 13. *(See Theorem 3.6 in [Bo]) Suppose that Γ_0 is a finitely generated group that acts isometrically, properly discontinuously, and cocompactly on a Riemannian manifold X . Let S be a (symmetric) generating set for Γ_0 . Let $x_0 \in X$. Then there are constants $0 < c < C$ so that*

$$cd_X(x_0, gx_0) \leq w_S(g) \leq Cd_X(x_0, gx_0) + C.$$

Applying Lemma 12 to equation (1), we see that

$$w_S(n') \leq C_1 R + C_2.$$

Rearranging the formula, we get a lower bound

$$R \geq c_1 w_S(n') - C_3. \tag{2}$$

Next we prove a lower bound on the word length $w_S(n')$.

Lemma 14. *Let D, Γ_1, Γ_N , and S be as above. Then there is a constant $c > 0$ so that any non-identity element $n' \in \Gamma_N$ has $w_S(n') \geq c \log N$.*

Proof. Let n' be a non-identity element of Γ_N . Write $n' = A' + B'\sqrt{2}$ where A', B' are matrices with integer coefficients. Since n' is not just the identity, one of the entries of A' or B' must have norm at least $N - 1$.

Let $M_1 = A_1 + B_1\sqrt{2}$ and $M_2 = A_2 + B_2\sqrt{2}$ be matrices, where A, B have integer coefficients. Write the product as $M = A + B\sqrt{2}$. We write $|M_1|$ for the maximum of the entries in A_1 or B_1 , and $|M_2|$ and $|M|$ similarly. Then a direct computation gives $|M| \leq C|M_1||M_2|$.

Now let s_1, s_2, \dots, s_T be the matrices in S . Write $s_i = A_i + B_i\sqrt{2}$ where A_i, B_i are integer matrices. Consider a product of w elements of S : $g = s_{i_1} \circ \dots \circ s_{i_w}$. Using the product estimate in the last paragraph repeatedly, we get $|g| \leq C^{w-1}(\max_{s_i \in S} |s_i|)^w \leq C_2^w$. Applying this argument to n' , we see that $N - 1 \leq C_2^{w_S(n')}$. Taking logarithms finishes the proof. \square

Plugging into equation (2), we get $R \geq c_1 \log N - C_2$. This finishes the proof of the Proposition. \square

Remark 15. The proof of Proposition 10 also shows that Γ_N acts without fixed points for all N large enough. During the proof we showed that for any $x \in \mathbb{H}^D$ and any $\gamma \in \Gamma_N$, the distance from x to $\gamma(x)$ is at least $c_1 \log N - c_2$. If N is sufficiently large, this distance is positive, and so Γ_N has no fixed points.

For what is needed for our construction of quantum codes, the above example $SO_f(\mathbb{Z}[\sqrt{2}])$ and Proposition 10 suffices. But let us take the opportunity to put on record a general result of this kind which is valid for all simple Lie groups.

Recall that if G is a simple Lie group and Γ is a discrete subgroup, then Γ is an arithmetic subgroup if there exists a number field k , a k -algebraic group H , and an epimorphism $\phi : H(k \otimes_{\mathbb{Q}} \mathbb{R}) \rightarrow G$ with compact kernel such that $\phi(H(O))$ is commensurable to Γ where $H(O)$ is the O -points of H with respect to some fixed embedding of H into $GL(m)$. ($H(O)$ depends on this embedding only up to commensurability.) If I is a non-zero ideal of O , then $H(O)_I$ is the kernel of the homomorphism from $H(O)$ to $H(O/I)$. Then $\Gamma(I)$ is defined to be $\phi(H(O)_I) \cap \Gamma$. A subgroup of Γ is called a congruence subgroup if it contains $\Gamma(I)$ for some (non-zero) ideal $I \subset O$. The collection of congruence subgroups of Γ does not depend on the embedding of H in $GL(m)$. We can now state:

Proposition 16. *Let G be a simple Lie group with maximal compact subgroup K , and let X be the symmetric space G/K . Let Γ be an arithmetic subgroup of G . Then there exists a constant $c_1 > 0$ so that for every normal congruence subgroup $N \subset \Gamma$, the injectivity radius of $N \backslash X$ is at least $c_1 \log \text{Vol}(N \backslash X) - c_2$.*

For principal congruence subgroups, the proof is essentially the same as the proof of Proposition 10. For arbitrary normal congruence subgroups, one should use the argument given in [LL], page 459, which shows that every normal congruence subgroup is “very close” to being a principal congruence subgroup. It is worth noting that in Proposition 16, we need the group N to be both normal and a congruence subgroup.

Suppose that N is normal but not congruence. For every D , there exists an arithmetic lattice in $SO(D, 1)$ which is mapped onto \mathbb{Z} (cf. [Mi] or [L2]). Taking finite cyclic covers induced by the maps $\mathbb{Z} \rightarrow \mathbb{Z}/N\mathbb{Z}$ will give normal covers with a bounded injectivity radius.

Now we consider examples that are congruence subgroups but not normal. Fix $\gamma \in \Gamma$, an element of infinite order. We consider a sequence of smaller and smaller ideals $I \subset O$. For each I , we let $\pi_I : H(O) \rightarrow H(O/I)$. Then we let Λ_I be $\pi_I^{-1}(\langle \pi_I(\gamma) \rangle)$. In words, Λ_I is the preimage of the subgroup generated by $\pi_I(\gamma)$. Clearly Λ_I contains γ for all I . Therefore, $\Lambda_I \backslash X$ contains a non-contractible loop of length independent of I . But the Λ_I are all congruence subgroups of Γ , and the index of Λ_I in Γ goes to infinity like a power of $[O : I]$.

4.2. Anderson’s systolic bound. Finally, we need an important result from hyperbolic geometry that connects the systoles of a hyperbolic manifold and its injectivity radius.

Theorem 17. *(Anderson, [A]) Let (M^D, hyp) be a closed manifold with a hyperbolic metric. Let $Z^i \subset M$ be a homologically non-trivial i -cycle with coefficients in \mathbb{Z}_2 . Let R be the injectivity radius of (M, hyp) . Then the volume of Z is at least the volume of a ball of radius R in the i -dimensional hyperbolic space. In particular, if $i \geq 2$ and $R \geq 1$, then $\text{Vol}_i(Z) \geq c(i)e^{(i-1)R}$.*

Remark 18. This theorem holds for any dimension i in the range $1 \leq i \leq D - 1$. But the main interest is in the range $2 \leq i \leq D - 1$. If $i = 1$, then a 1-dimensional hyperbolic ball of radius R is just an interval $[-R, R]$, and it has 1-dimensional volume $2R$. But for each

$i \geq 2$, the i -volume of an i -dimensional hyperbolic ball of radius R grows exponentially in R , roughly like $e^{(i-1)R}$.

Remark 19. Anderson's original results are stated for integral cycles, but essentially the same proof works also with coefficients in \mathbb{Z}_2 - see Section 5 where we discuss some of the main ideas of the proof.

Now we have all the tools to prove Theorem 6.

Proof. Let M_1 and M_N be as above. By Proposition 10 the injectivity radius of M_N is $R_N \geq c \log \text{Vol } M_N$. By Anderson's theorem, every homologically non-trivial mod 2 2-cycle in M_N has area $\geq ce^{R_N} \geq c \text{Vol } M_N^c$.

On the other hand, using the Gauss-Bonnet-Chern theorem, we already proved that $\text{Dim } H_2(M_N) \geq (2/\text{Vol } S^4) \text{Vol } M_N - 2$. By taking N sufficiently large, we get $\text{Dim } H_2(M_N) \geq (1/100) \text{Vol } M_N$ as desired. \square

Remark 20. The proof shows that the distance of our code is at least $n^{\epsilon''}$ for some $\epsilon'' > 0$. On the other hand, the distance is at most $O(n^{0.3})$. This is because our lattice Γ_N contains an arithmetic lattice Λ_N of $SO(2, 1)$. (In fact, every arithmetic lattice in $SO(4, 1)$ contains an arithmetic lattice of $SO(2, 1)$ - see [L1].) Hence every $M_N = \Gamma_N \backslash \mathbb{H}^4$ contains the surface $\Lambda_N \backslash \mathbb{H}^2$. While the volume of $\Gamma_N \backslash \mathbb{H}^4$ grows like N^{20} , the area of $\Lambda_N \backslash \mathbb{H}^2$ grows like N^6 . See Proposition 3.2 in [B] for more details of a similar argument.

5. ON ANDERSON'S THEOREM

The proof uses minimal surface theory. A complete proof (including all the underlying results from minimal surface theory) is somewhat long, but we can explain the basic ideas behind the proof. We will explain first the original proof with \mathbb{Z} coefficients, and at the end we discuss what to do in the \mathbb{Z}_2 case.

The first main idea is to replace Z with a surface of minimal area Z_{min} in its homology class. A serious result from minimal surface theory is that there is a kind of generalized surface - a stationary integral current - in the homology class of Z with minimal volume. An integral current is a generalization of an integral chain which can be somewhat more singular. It suffices to prove a lower bound for $\text{Vol}_k Z_{min}$. Since Z is homologically non-trivial, Z_{min} is not empty. Minimal surfaces have special geometric properties that can be used to estimate the volume of Z_{min} .

The proof is based on the hyperbolic generalization of the monotonicity theorem for minimal surfaces. For context we first recall the standard monotonicity theorem for minimal surfaces in \mathbb{R}^n .

Theorem 21. (*Monotonicity*) *Let X be an integral k -chain in \mathbb{R}^n . Suppose that X has the smallest volume of any chain with boundary ∂X . Suppose that ∂X lies in $\partial B^n(R)$. Then the ratio*

$$\frac{\text{Vol}_k(X \cap B^n(r))}{\text{Vol}_k B^k(r)}$$

is non-decreasing for $0 < r \leq R$.

In this formula, $B^k(r)$ is the Euclidean k -ball of radius r . If X contains 0, and if X is a smooth manifold in a small neighborhood of 0, then the volume ratio goes to 1 as $r \rightarrow 0$. Then the monotonicity theorem guarantees that the volume ratio is ≥ 1 for all r . So we see that if 0 is a smooth point of X , then $\text{Vol}_k X$ is at least the volume of the Euclidean k -ball of radius R .

We will explain the idea of the proof of the monotonicity theorem below. Now we give the hyperbolic analogue.

Theorem 22. (*Anderson [A]*) *Let X be an integral k -chain in the hyperbolic space \mathbb{H}^n . Suppose that X has the smallest volume of any chain with boundary ∂X . Let $B_{hyp}^n(R) \subset \mathbb{H}^n$ denote the hyperbolic ball of radius R . Suppose that ∂X lies in $\partial B^n(R)$. Then the ratio*

$$\frac{\text{Vol}_k(X \cap B_{hyp}^n(r))}{\text{Vol}_k B_{hyp}^k(r)}$$

is non-decreasing for $0 < r \leq R$.

In particular, if X contains the center of the ball $B_{hyp}^n(R)$ and X is a smooth manifold near that point, then $\text{Vol}_k X$ is at least the volume of a k -dimensional hyperbolic ball of radius R .

Anderson's theorem is deduced quickly from Theorem 22. The stationary integral current Z_{min} as before can have singularities, but a fundamental result of geometric measure theory says that almost every point is regular, i.e. it has a neighborhood where Z_{min} is a smooth submanifold. We pick one such point x . We consider the intersection of Z_{min} with the ball around x of radius R equal to the injectivity radius of (M, hyp) . This ball is isometric to the ball of radius R in \mathbb{H}^n . By the monotonicity theorem, the volume of Z_{min} in this ball is at least the volume of a k -dimensional hyperbolic ball of radius R .

Let us now give the main idea of the proof of Theorems 21 and 22.

The monotonicity theorem is based on the formula for the volume of a cone. Let Y^{k-1} be a surface in $\partial B^n(r) \subset \mathbb{R}^n$. We let CY denote the cone over Y with vertex at the origin. This is the union of all the line segments with one endpoint at the origin (the center of $B^n(r)$) and the other endpoint on Y . The formula for the volume of a cone is as follows:

$$\text{Vol}_k CY = (r/k) \text{Vol}_{k-1}(Y).$$

Here is one way of thinking about this formula. Because of the symmetry of the sphere and the ball, we must have a formula of the type $\text{Vol}_k CY = \text{Const}(r, k) \text{Vol}_{k-1} Y$. Then we can evaluate $\text{Const}(r, k)$ by looking at the simplest example: when CY is a k -dimensional ball of radius r and Y is a $(k-1)$ -dimensional sphere of radius r . Let $VB_k(r)$ be the volume of a k -dimensional ball of radius r and $VS_{k-1}(r)$ be the volume of a $(k-1)$ -sphere of radius r . We get

$$\text{Vol}_k CY = \frac{VB_k(r)}{VS_{k-1}(r)} \text{Vol}_{k-1} Y. \quad (1)$$

The ratio $VB_k(r)/VS_{k-1}(r)$ is equal to r/k because the volume of a k -dimensional cone is $(1/k)$ times the volume of the base times the height. But in fact Equation (1) is more useful than the formulation with r/k .

We return to the monotonicity formula. We let $X \subset B^n(R)$ be our minimal chain. We let $X_r := X \cap B^n(r)$ and we let $Y_r = \partial X_r$. Since X is minimal, X_r must also be minimal, and so

$$\text{Vol}_k X_r \leq \text{Vol}_k CY_r = \frac{VB_k(r)}{VS_{k-1}(r)} \text{Vol}_{k-1} Y_r. \quad (2)$$

The coarea inequality says that $\frac{d}{dr} \text{Vol}_k X_r \geq \text{Vol}_{k-1} Y_r$ (for almost every r). We let $V(r) := \text{Vol}_k X_r$, and the last equation becomes the following differential inequality.

$$V'(r) \geq \frac{VS_{k-1}(r)}{VB_k(r)} V(r). \quad (3)$$

Since $\frac{d}{dr} VB_k(r) = VS_{k-1}(r)$, Equation (3) implies:

$$\frac{d}{dr} \left(\frac{V(r)}{VB_k(r)} \right) \geq 0. \quad (4)$$

Indeed, by expanding the left hand side of (4) and plugging in (3), (4) is proven. Equation (4) is the monotonicity formula of Theorem 21.

The story above generalizes in a straightforward way to hyperbolic space. If Y is a $(k-1)$ -dimensional surface in the boundary of the hyperbolic ball of radius r , then by symmetry we get $Vol_k CY = const(r, k) Vol_{k-1} Y$ for all Y . We can evaluate $const(r, k)$ by looking at the example when CY is a hyperbolic k -dimensional ball of radius r . We let $VHB_k(r)$ denote the volume of a hyperbolic k -dimensional ball of radius r , and we let $VHS_{k-1}(r)$ denote the $(k-1)$ -volume of the boundary of the ball. We get

$$Vol_k CY = \frac{VHB_k(r)}{VHS_{k-1}(r)} Vol_{k-1} Y. \quad (1H)$$

We let X be our minimal chain in $B_{hyp}^n(R)$, with $\partial X \subset \partial B_{hyp}^n(R)$. We let $X_r := X \cap B_{hyp}^n(r)$, and we let $Y_r = \partial X_r$. By minimality, we get:

$$Vol_k X_r \leq Vol_k CY_r = \frac{VHB_k(r)}{VHS_{k-1}(r)} Vol_{k-1} Y_r. \quad (2H)$$

As before, $\frac{d}{dr} Vol_k X_r \geq Vol_{k-1} Y_r$. We let $V(r) := Vol_k X_r$. The last equation becomes the following differential inequality:

$$V'(r) \geq \frac{VHS_{k-1}(r)}{VHB_k(r)} V(r). \quad (3H)$$

Since $\frac{d}{dr} VHB_k(r) = VHS_{k-1}(r)$, Equation (3H) implies the hyperbolic monotonicity formula from Theorem 22:

$$\frac{d}{dr} \left(\frac{V(r)}{VHB_k(r)} \right) \geq 0. \quad (4H)$$

This concludes our description of some of the geometric ideas in the proof of Anderson's inequalities. What is missing is to prove that Z_{min} exists, and that Z_{min} is smooth at almost every point, and that Z_{min} is a sufficiently nice geometric object so that the reasoning above applies to it. This is a standard topic in geometric measure theory, and it takes a substantial amount of work. One can prove that Z_{min} exists for cycles with coefficients in either \mathbb{Z} or \mathbb{Z}_2 , but the arguments are slightly different. Working over \mathbb{Z}_2 one can use mod 2 flat cycles instead of integral currents. After proving the existence and some regularity of Z_{min} , the argument above will give the version of Anderson's theorem needed in the current paper.

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