The Surface Subgroup Theorem

and

The Ehrenpreis Conjecture

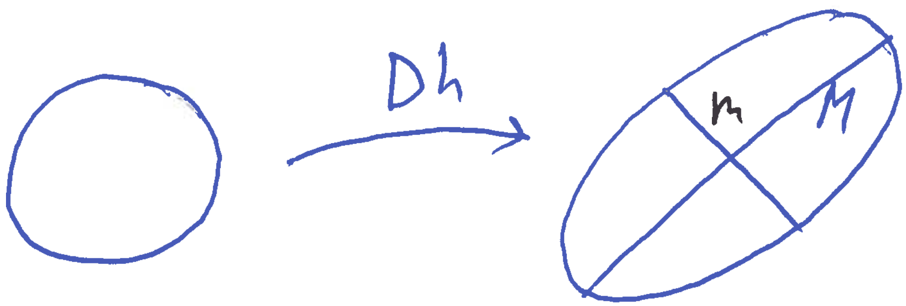
by Jeremy Kahn

Joint with Vladimir Markovic

Theorem (KM) (Ehrenpreis conjecture)
Let S and T be closed hyperbolic Riemann surfaces. Then S and T have nearby finite covers (in the Teichmuller metric).

Theorem (KM) (Ehrenpreis Conjecture)

Suppose S and T are closed hyperbolic Riemann surfaces, and $K > 1$. Then we can find finite covers $\hat{S}$ and $\hat{T}$ of S and T and a smooth K-quasiconformal map $h : \hat{S} \to \hat{T}$.



$$\frac{M}{m} \le K$$

<u>Theorem</u> (KM) (Surface subgroup Conjecture)

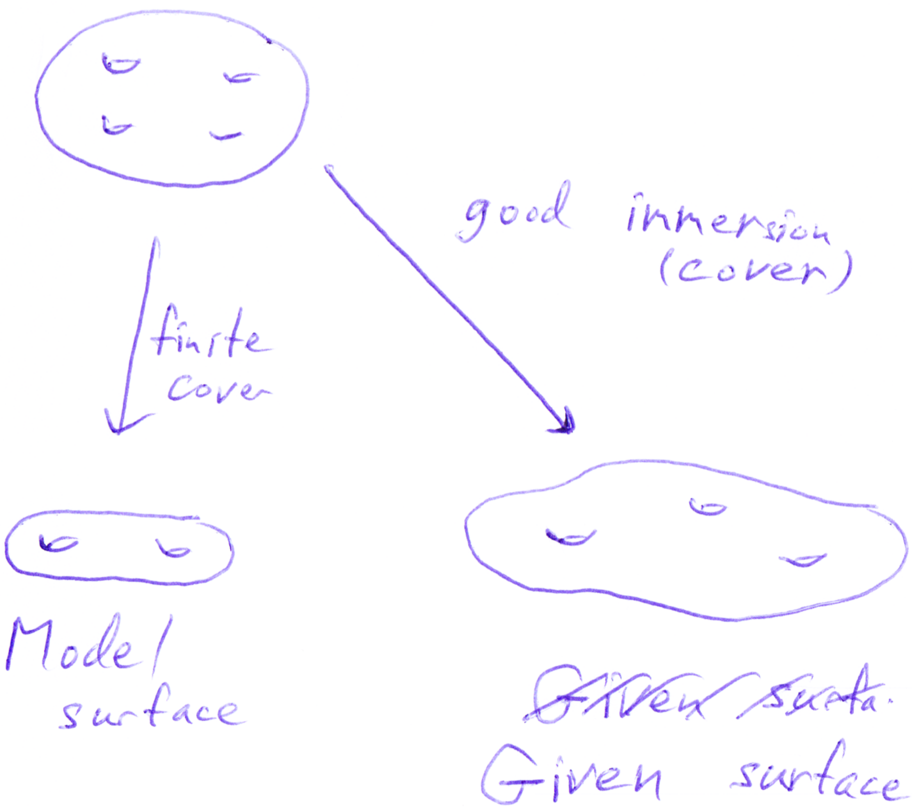
Let M be a closed hyperbolic 3-manifold. Then $\pi_1(M)$ has a surface subgroup (the isomorphic image of π_1 of a hyperbolic surface).

References

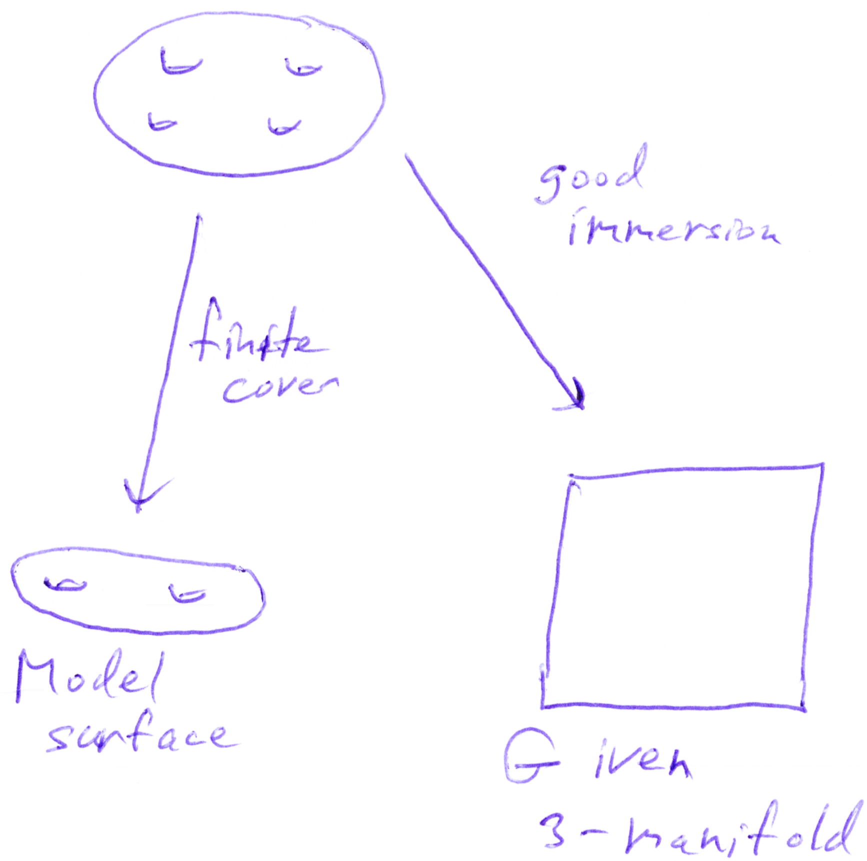
Immersing almost geodesic surfaces in a closed hyperbolic 3-manifold (to appear in Annals of Mathematics)

The good pants homology and a proof of the Ehrenpreis conjecture. (arXiv: 1101.1330).

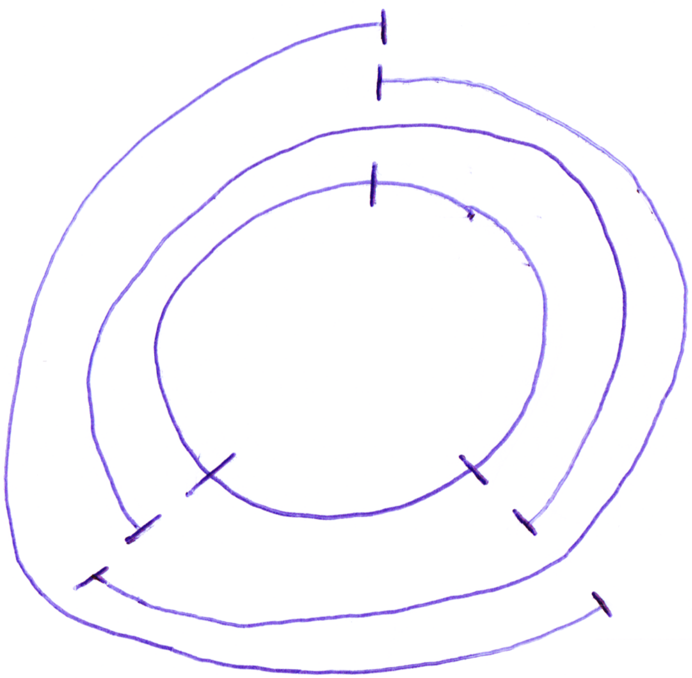
2D


good immersion (cover)
finite cover
Model surface
~~Given surfa.~~
Given surface

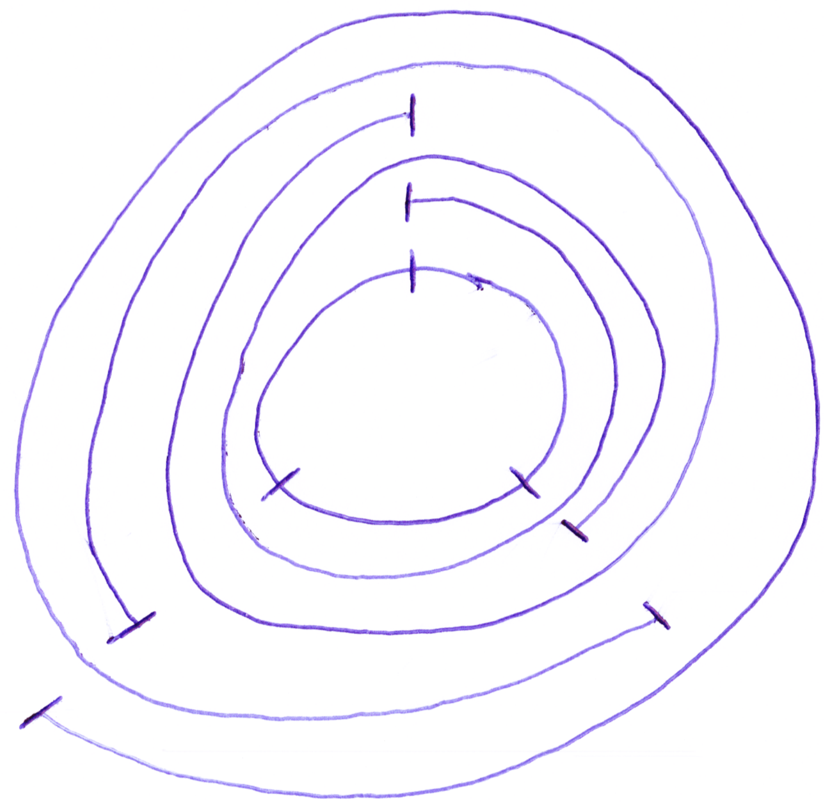
3D


good immersion
finite cover
Model surface
Given 3-manifold

Building Covers of the Circle



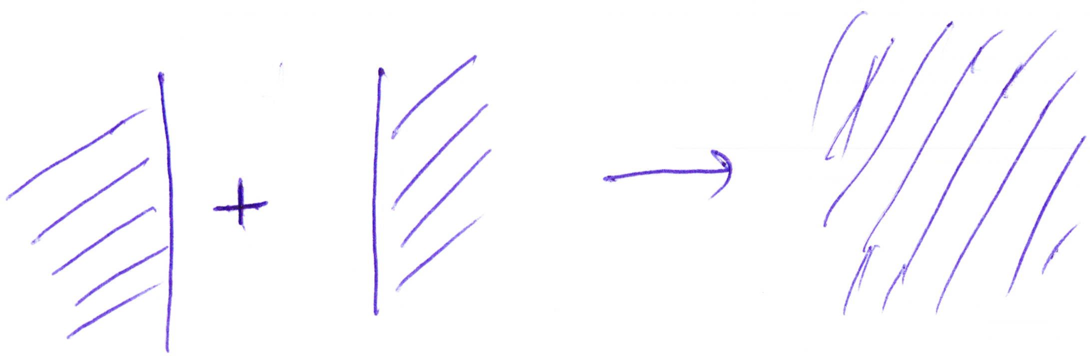
degree 2



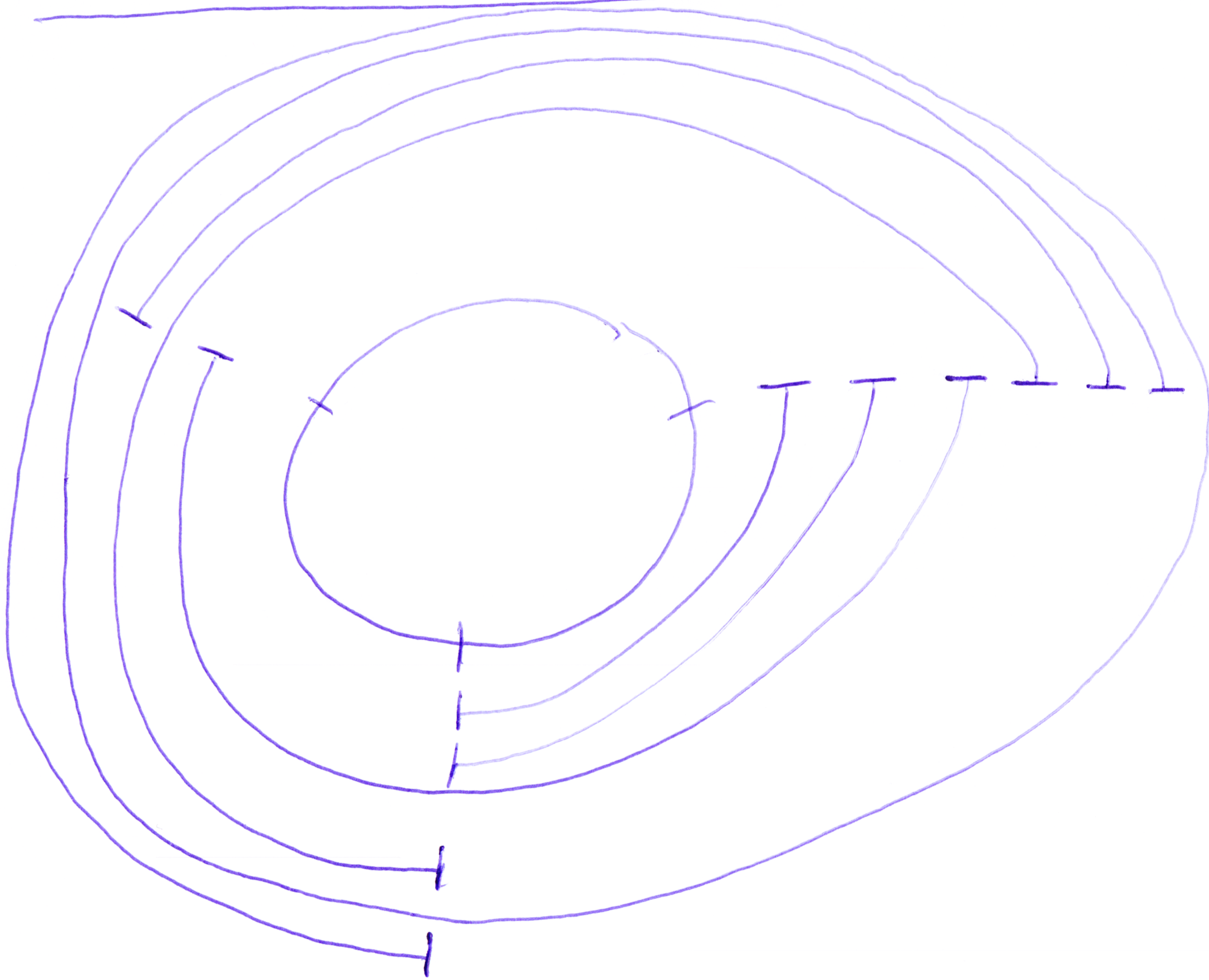
degree 4

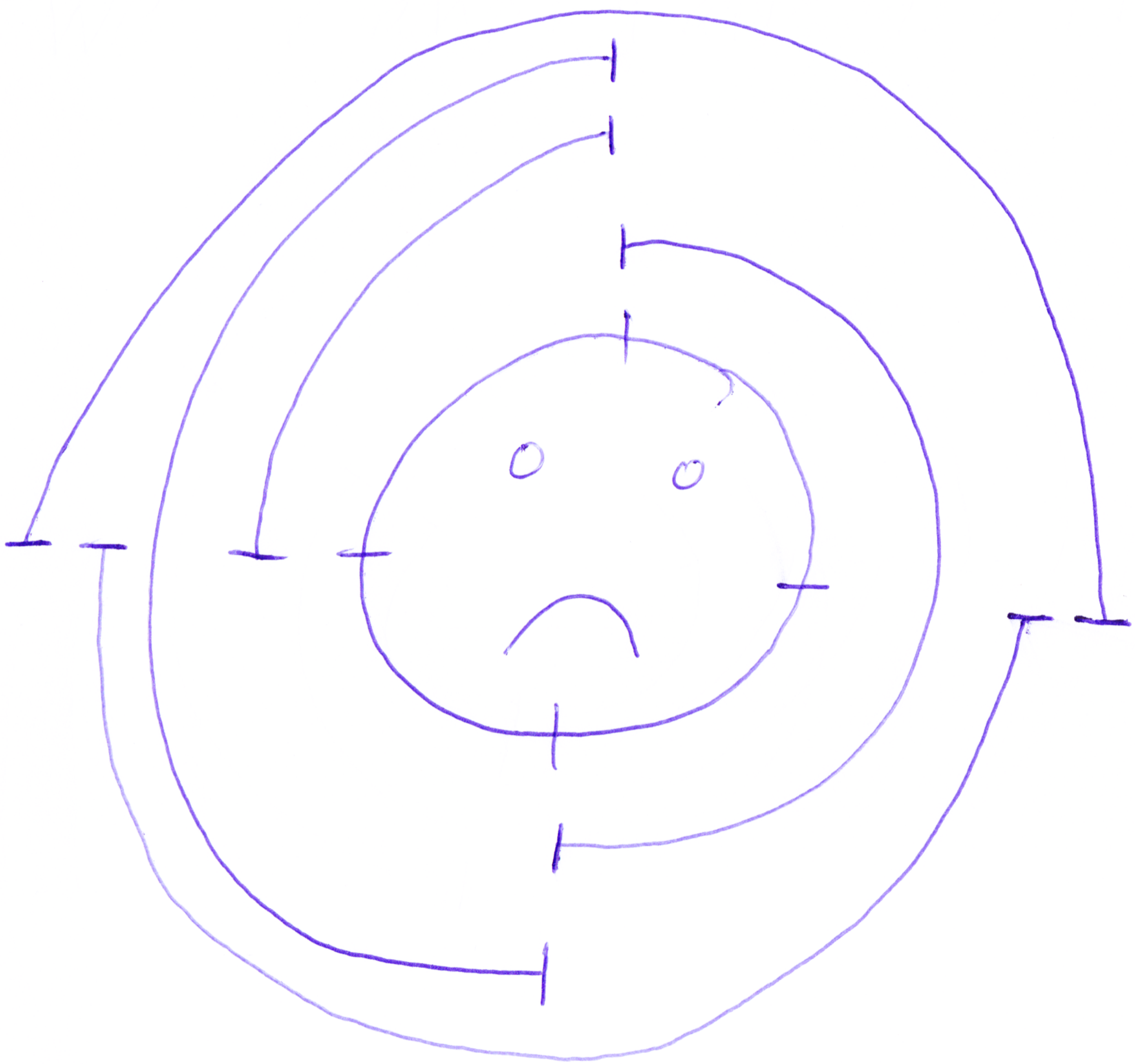
We can join immersed 1-manifolds with boundary to form a cover of a closed 1-manifold (a circle).

We can join immersed orientable n-manifolds with boundary to form a cover of a closed orientable n-manifold.



We can build more than one cover

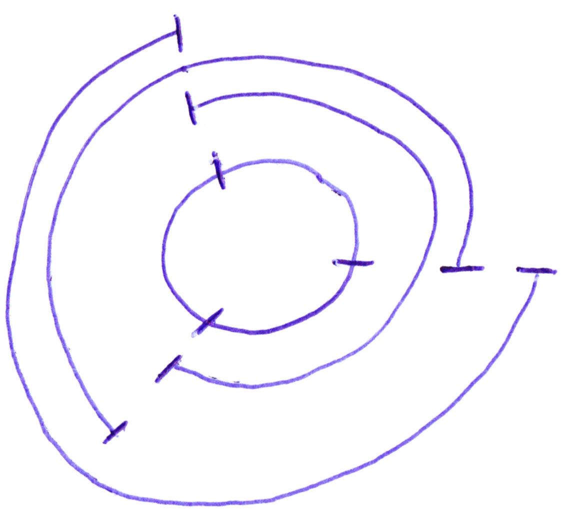




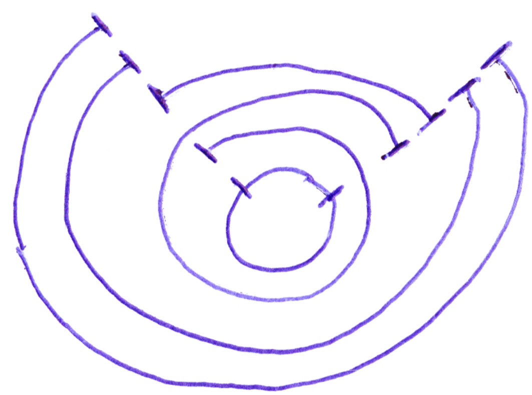
We can fail to build a cover

Given a collection $C = \sum n_i \alpha_i$ of 1-manifolds, immersed in a circle, we can assemble C to form a cover if and only if

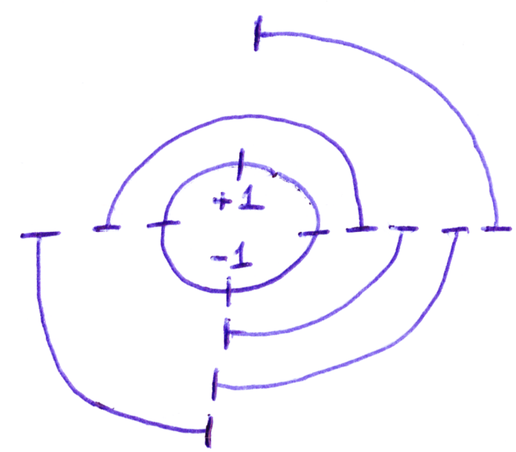
$$\partial C \equiv \sum n_i \partial \alpha_i = 0$$



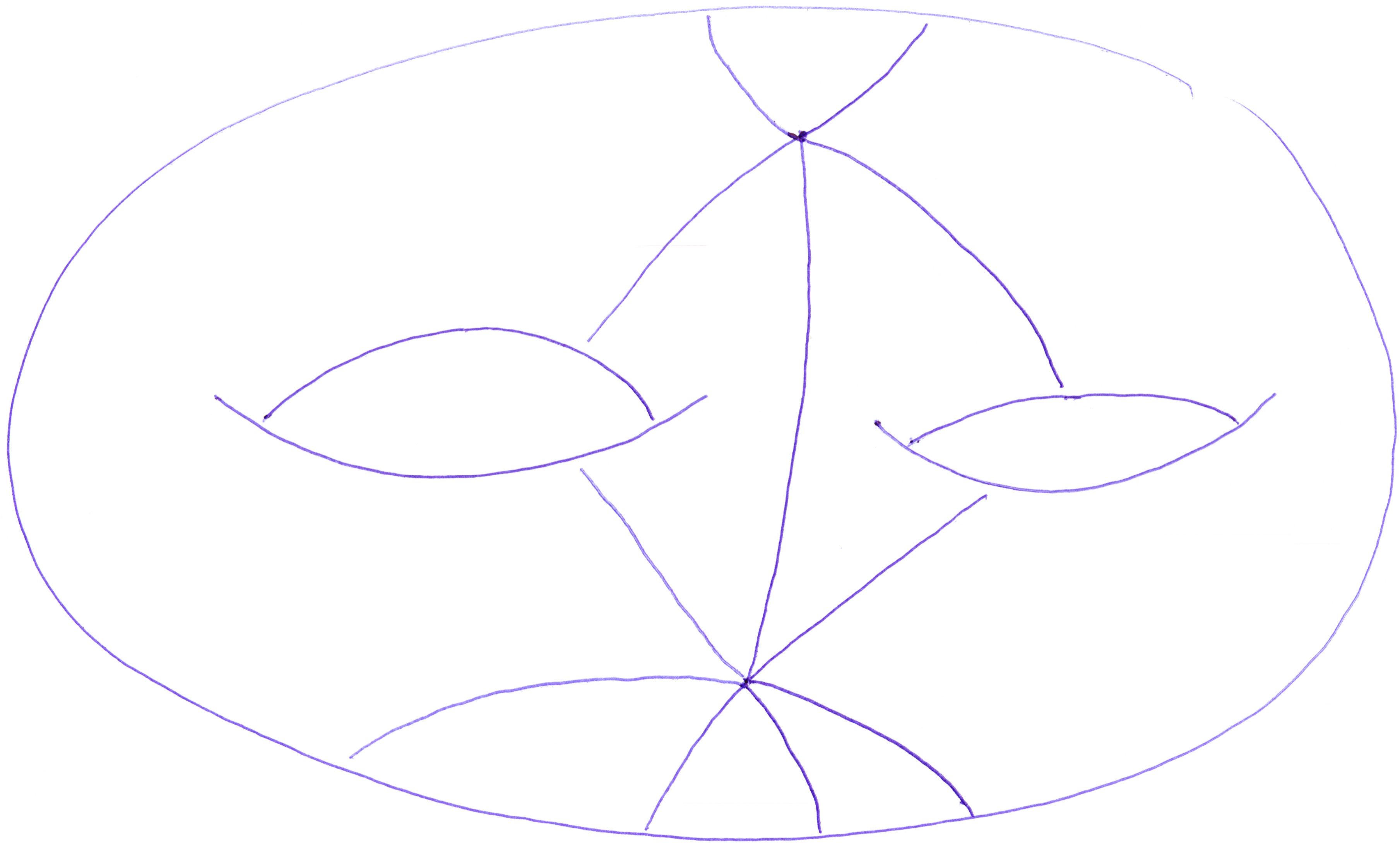
$\partial C = 0$



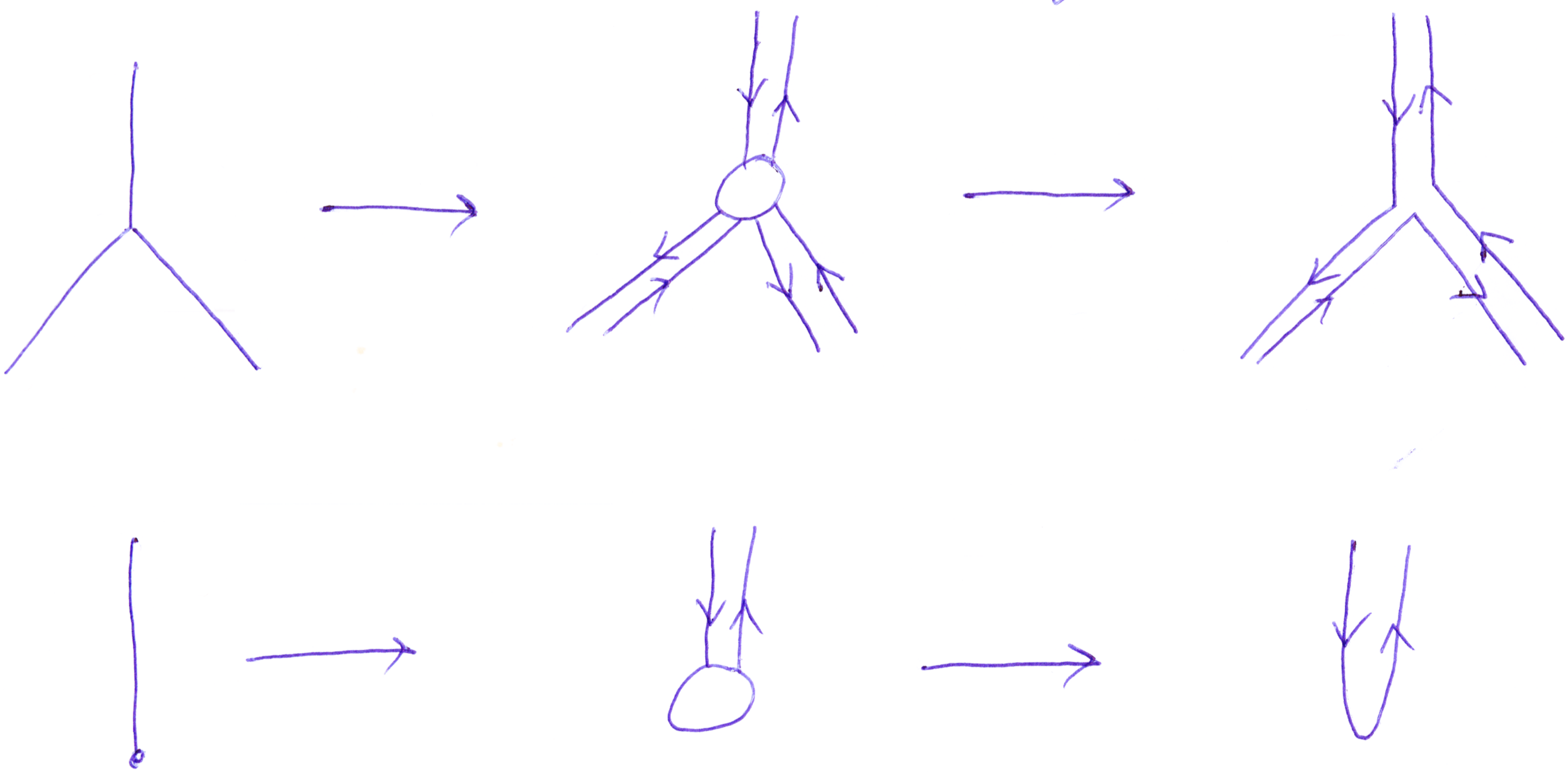
$\partial C = 0$

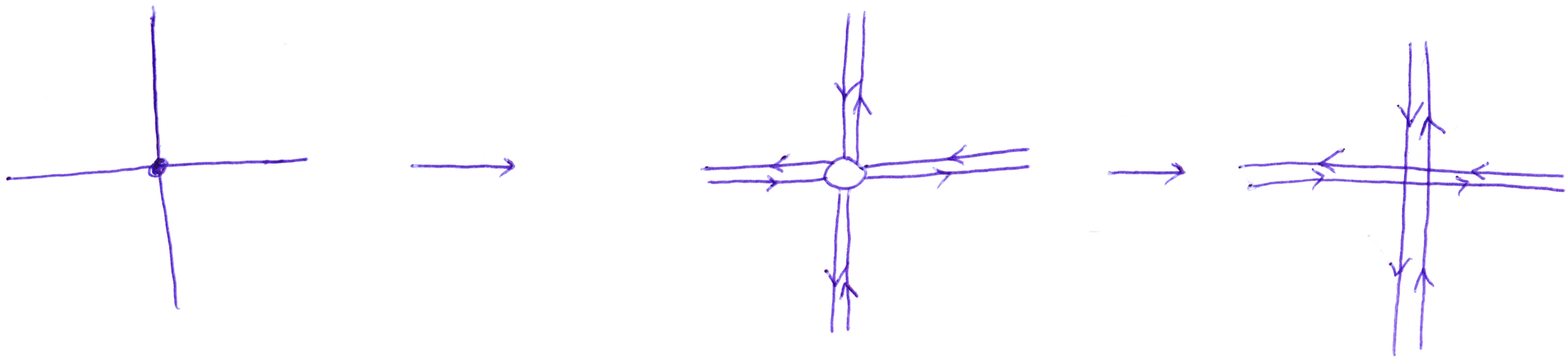


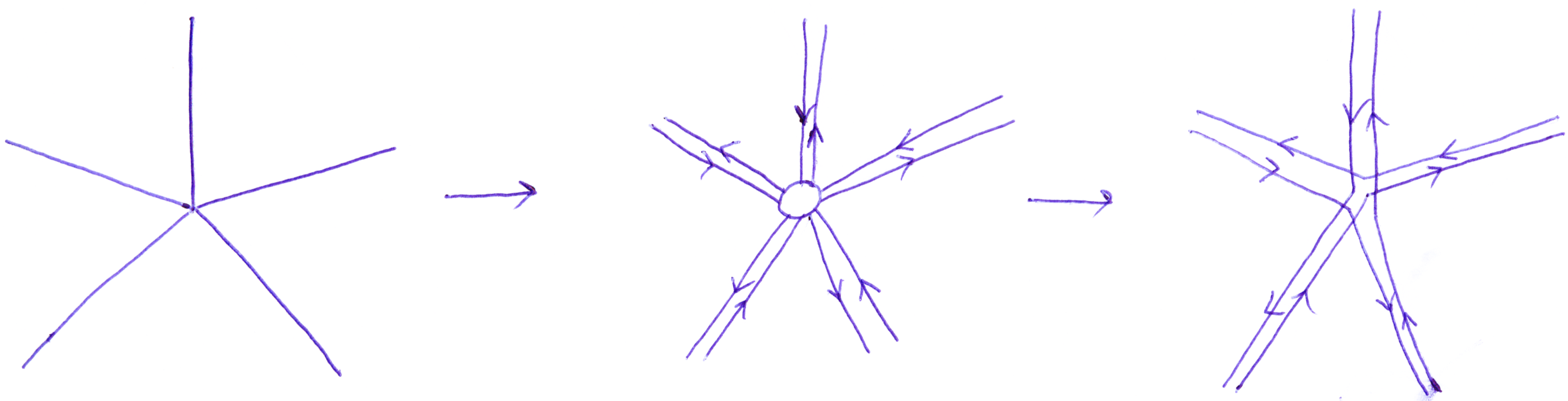
$\partial C \neq 0$



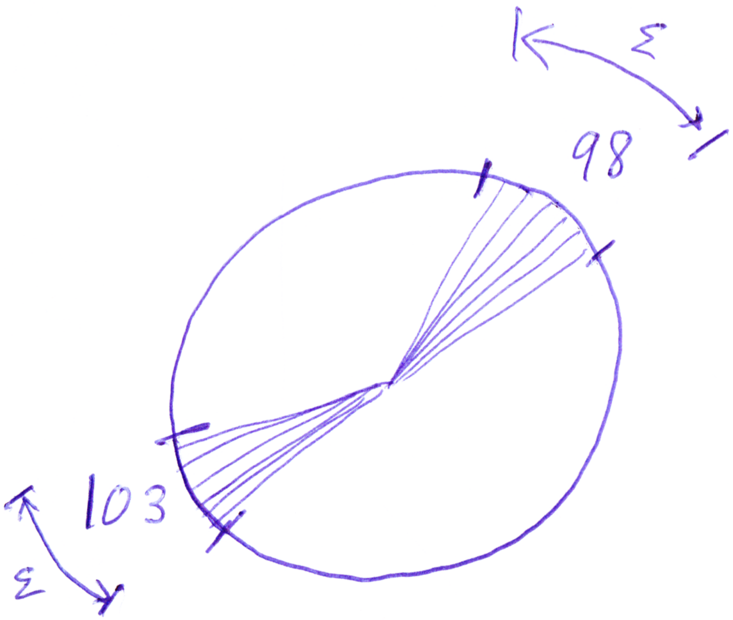
We can always build a piecewise immersed 1-manifold in a closed 2-manifold if we use the "doubling trick"





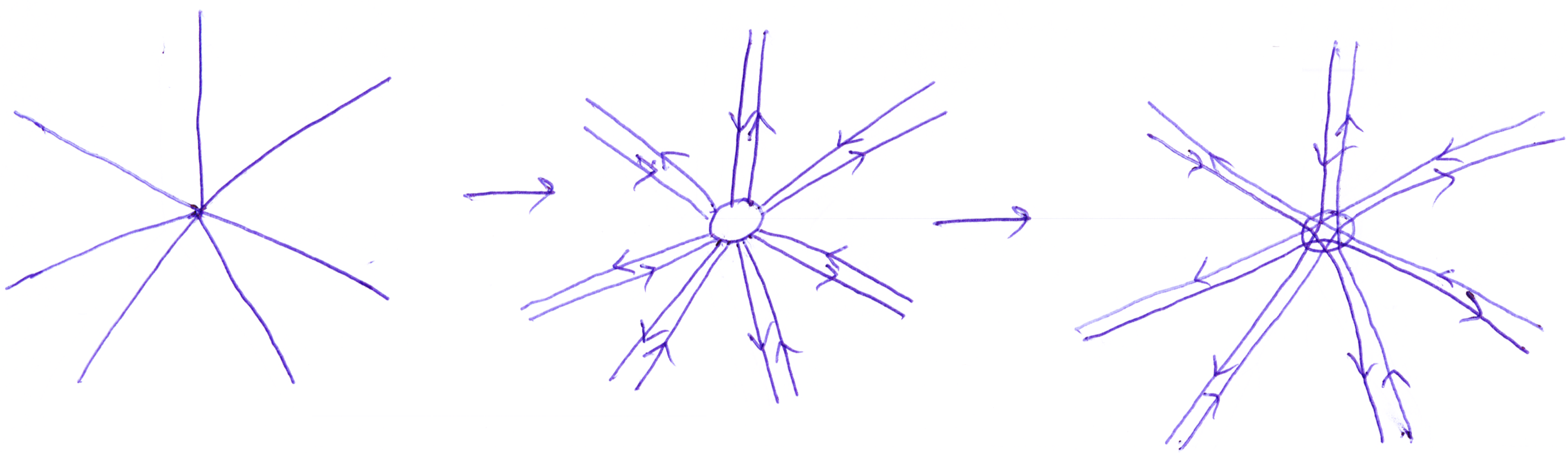


A set of points ~~of~~ on S^1 is "evenly distributed to the ~~scla~~ scale ε" if every ε-interval of S^1 has the same number of points, ~~to~~ up to a factor of $1+\varepsilon$.

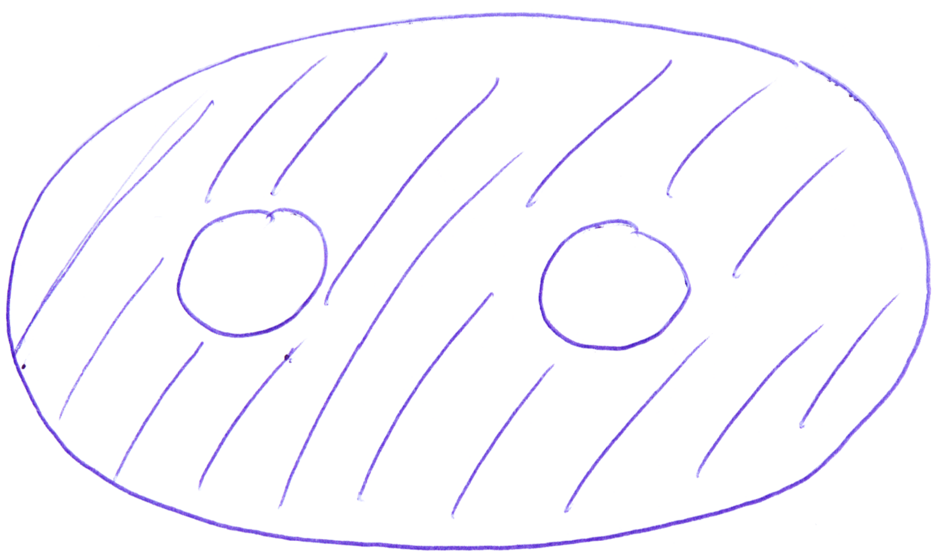


$$\frac{103}{98} < 1+\varepsilon$$

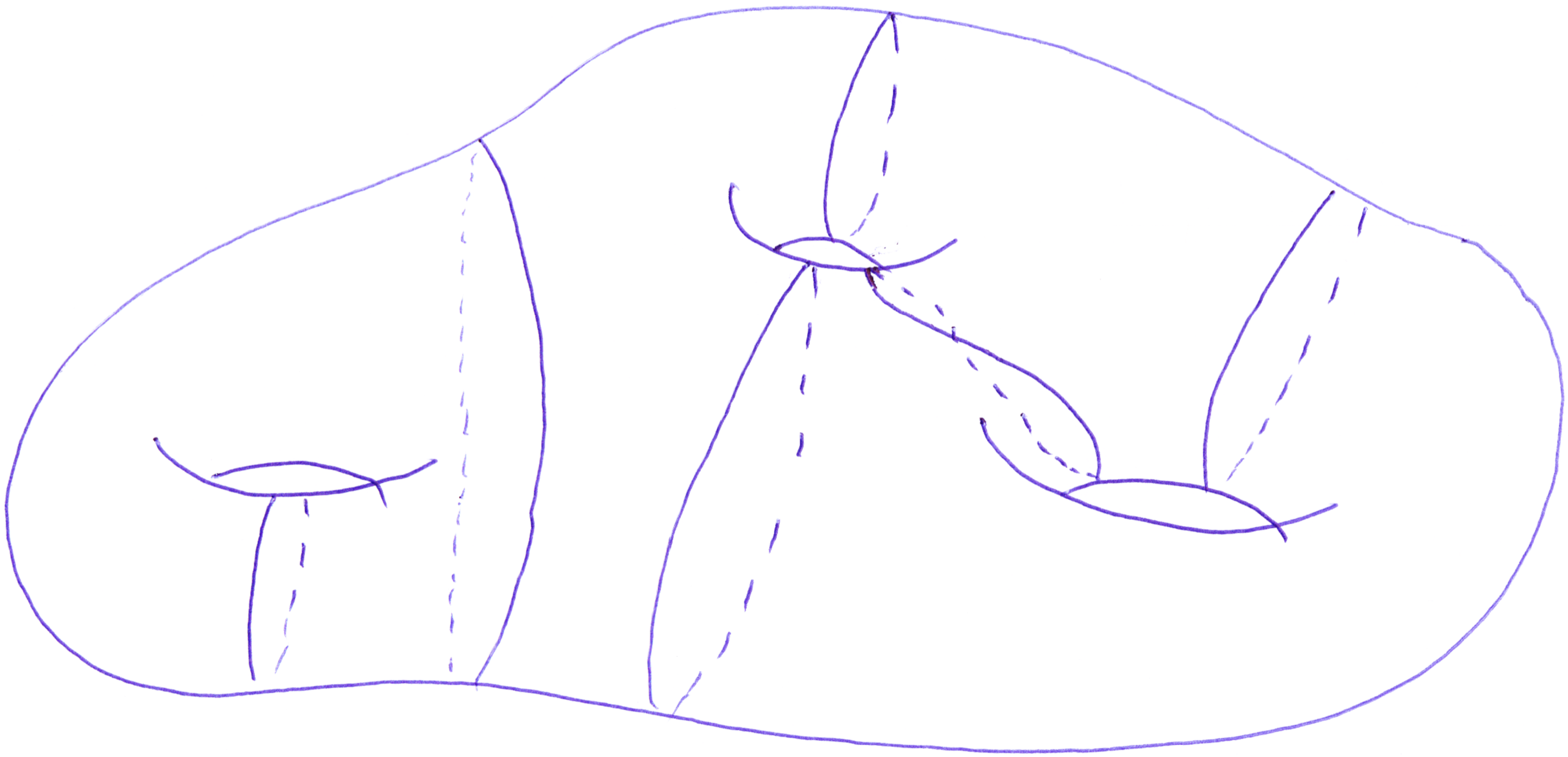
We can make the piecewise immersed 1-manifold nearly geodesic (small bending) if the segments are "evenly distributed" around each meeting ~~point:~~ point:



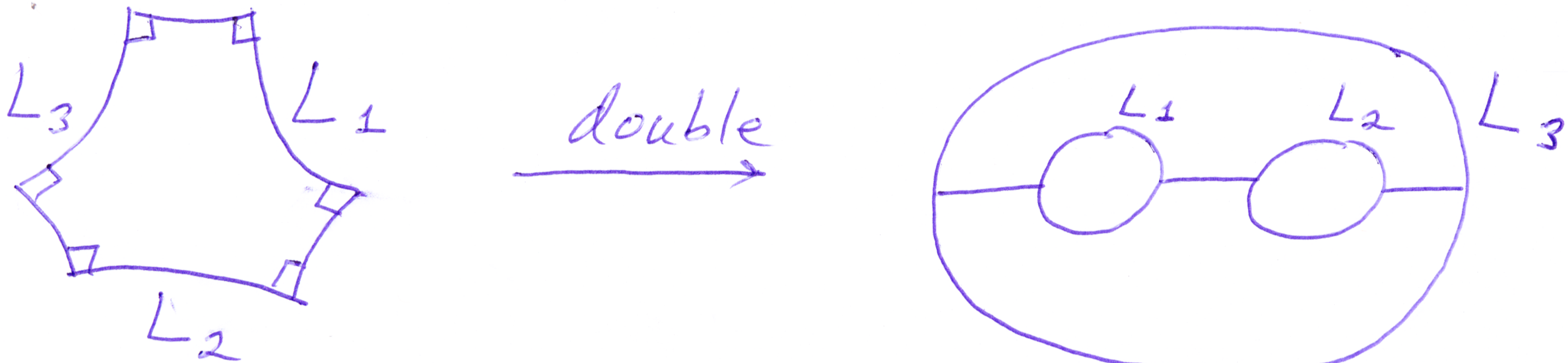
A (hyperbolic) pair of pants is a hyperbolic 2-manifold with geodesic boundary that is diffeomorphic to the following.



We obtain a closed hyperbolic surface when we join pairs of pants

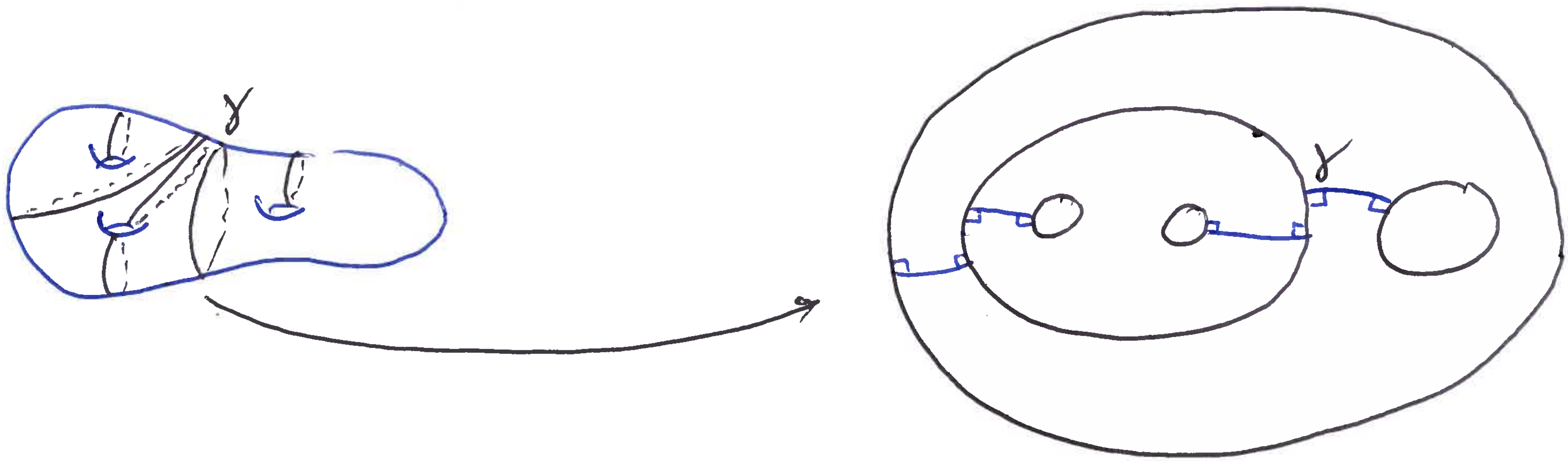


Hyperbolic Pairs of Pants

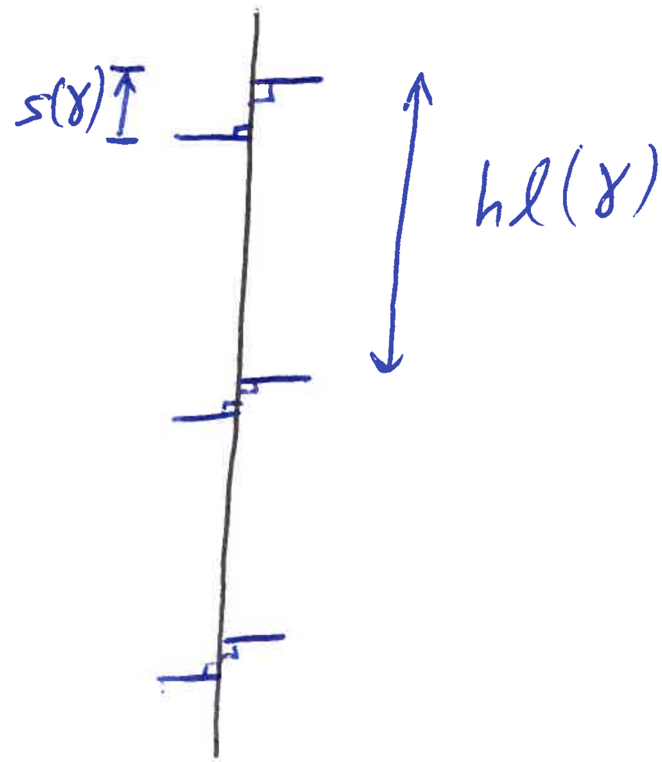


Half-lengths L_1, L_2, L_3

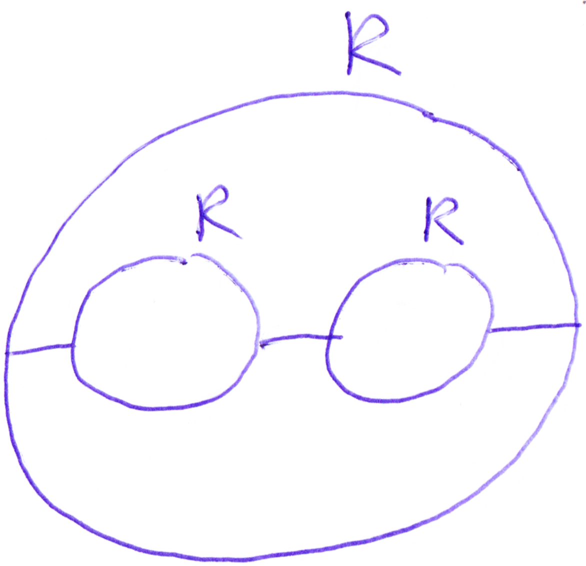
Shear Coordinates for Panted Surfaces

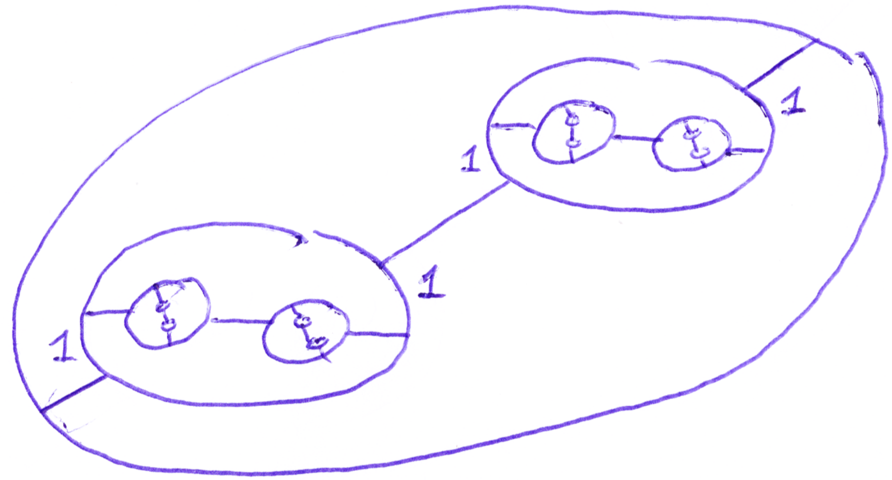


$$s(\gamma) \in \mathbb{R} / h\ell(\gamma)\mathbb{Z}$$



Perfect Pants and Perfect Surfaces



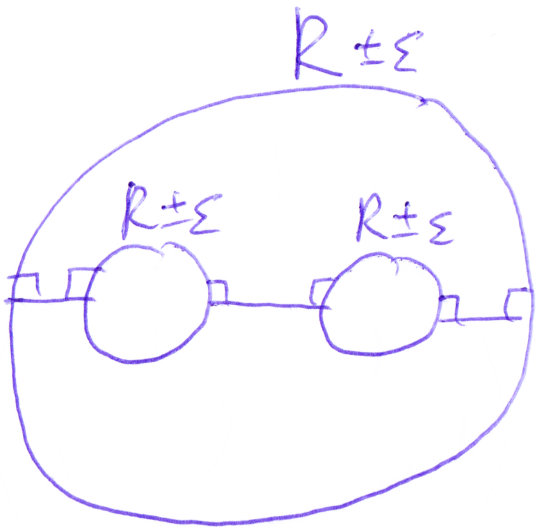


$hl(C) = R$

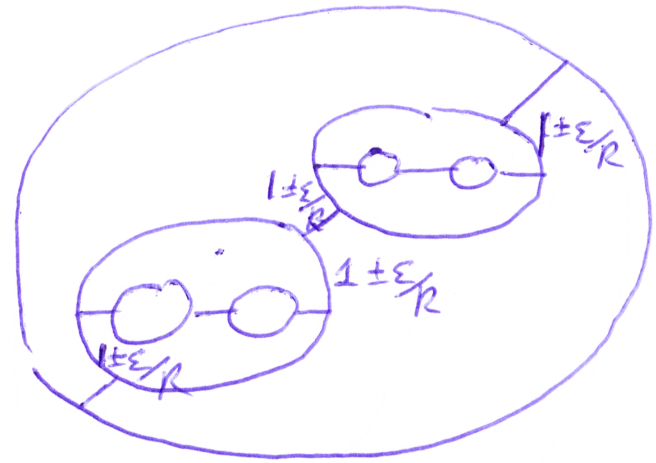
$hl(C) = R$
$s(C) = 1$

<u>Theorem</u> Any two closed ~~surfaces~~ perfect surfaces have a common finite cover.

Good Pants and Good Surfaces



$$|\mathbf{hl}(C) - R| < \varepsilon$$



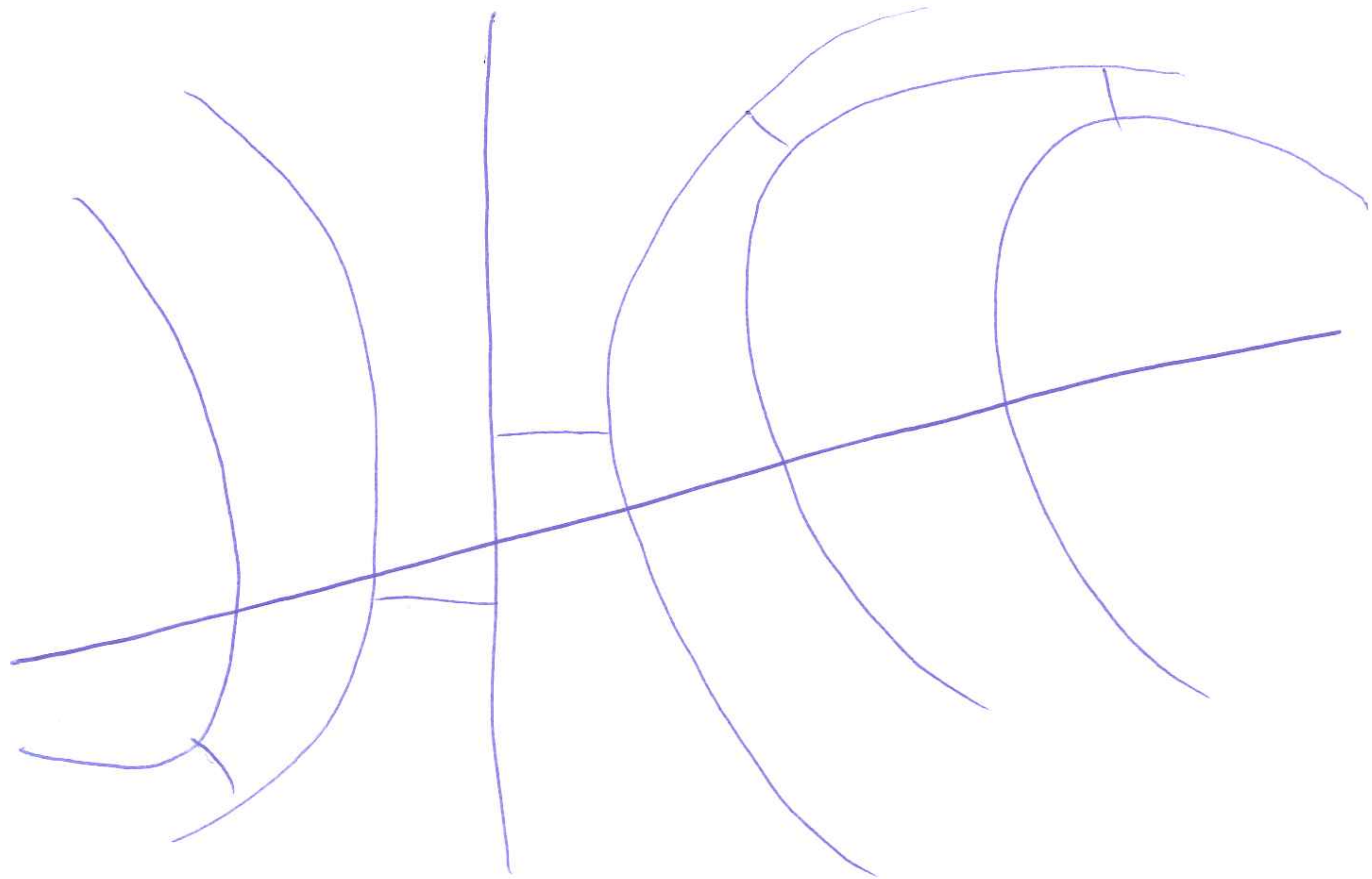
$$|s(C) - 1| < \frac{\varepsilon}{R}$$

<u>Theorem</u> (KM) ~~An~~
A good closed panted surface is close to a perfect surface.

Theorem (KM)

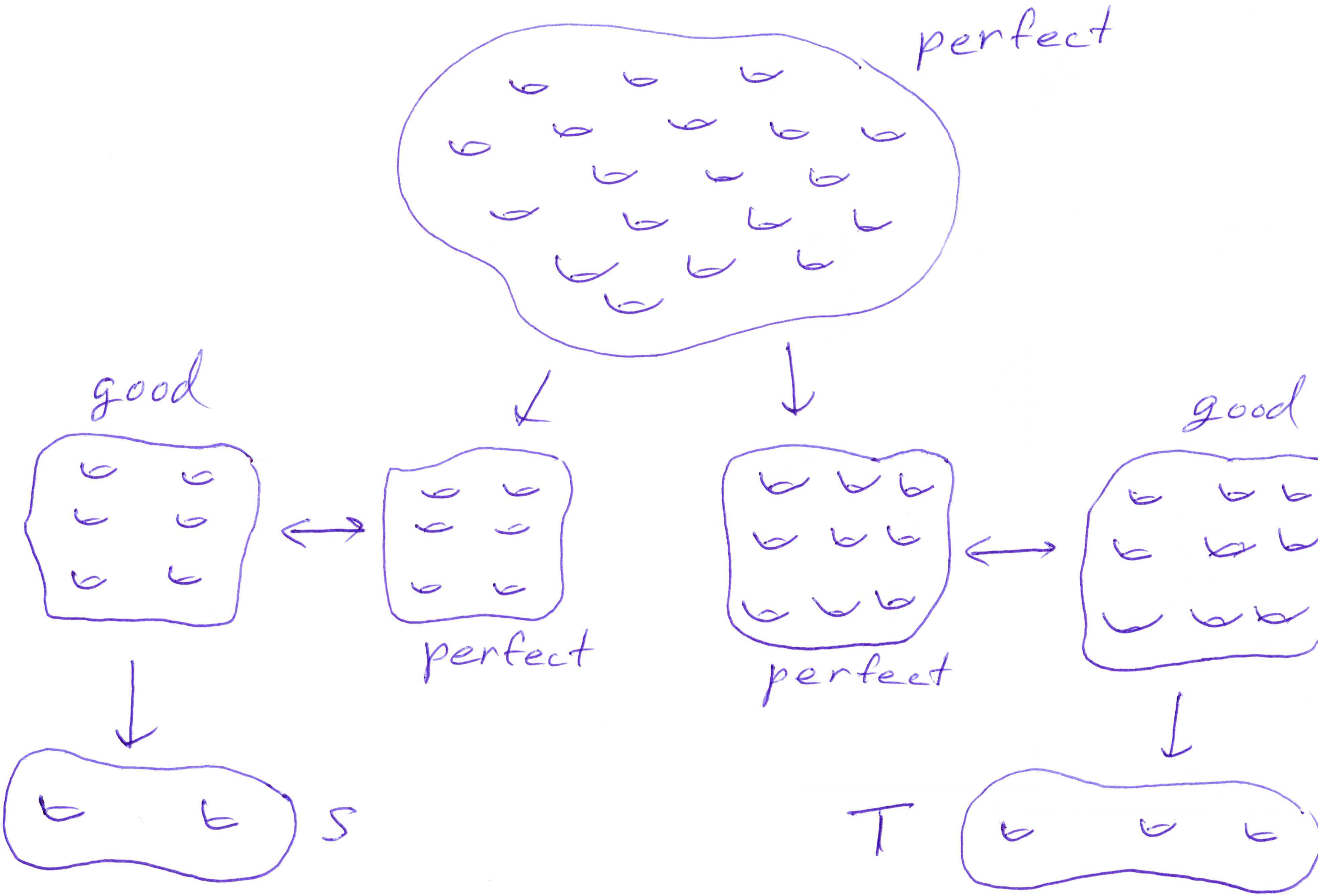
For all $\varepsilon < \varepsilon_0$, and $R > R_0$, any (ε, R) good surface is $10^{12}\varepsilon$-close to an R-perfect surface in the Teichmuller metric.

Adding the effects of the errors



At most 100R shears ~~&~~ with ~~erro~~ error less than ε/R $\Rightarrow$ Total error less than ε.

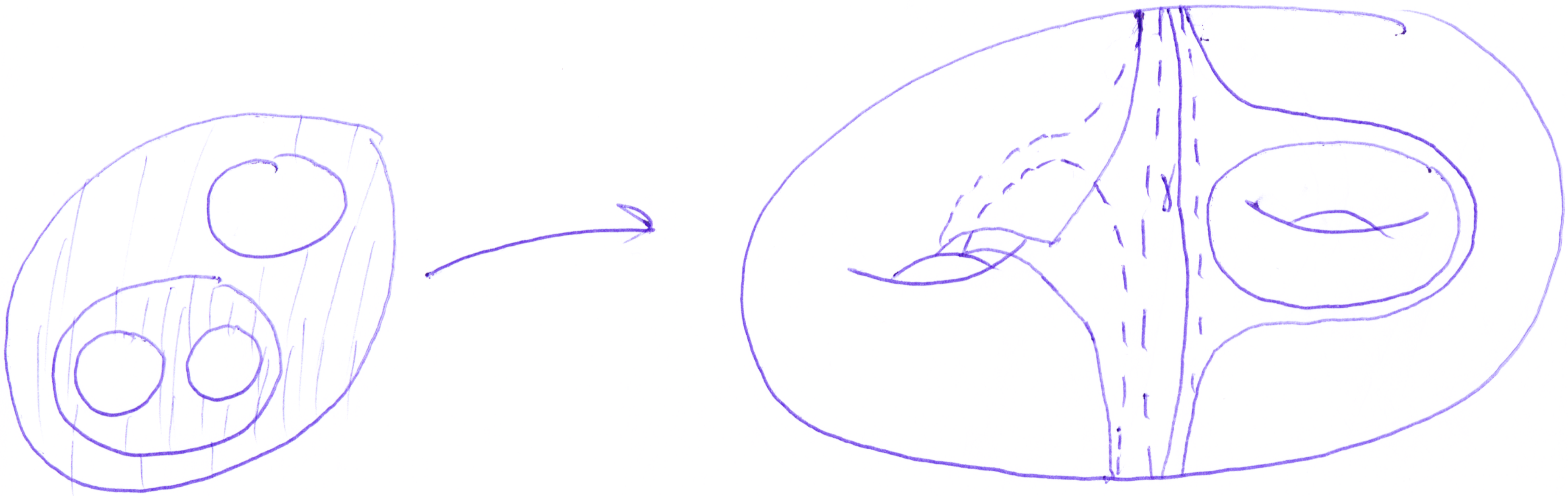
Good Covers ⇒ Ehrenpreis



An Immersed Pair of Pants

We can think of the pants as being isometrically immersed, and speak of the goodness of pants.

Gluing Together Immersed Pants



We can ~~ind~~ ~~in~~ identify cuffs of the parametrizing pants whenever the cuffs map to the same ~~go~~ geodisic γ, and the pants are on <u>opposite sides</u> of γ.

Easy Theorem

Let Q be a finite set of immersed pants, such that for every closed geodesic γ on S we have the same number of pants on both sides of γ. (That number can be zero). Then we can assemble Q to form a finite cover of S.

Good Pants and Good Curves

We let

$$\Gamma_{\varepsilon,R} = \left\{ \gamma \,\middle|\, \begin{array}{l} \gamma \text{ is a closed geodesic on } S \\ |hl(\gamma) - R| < \varepsilon \end{array} \right\}$$

$$\Pi_{\varepsilon,R} = \left\{ P \,\middle|\, \begin{array}{l} P \text{ is an immersed pair} \\ \text{of pants in } S, \text{ and} \\ \partial P \subseteq \Gamma_{\varepsilon,R} \end{array} \right\}$$

Things to Remember

1. We fix S and ε throughout the discussion

2. We take $R \geq R_0(S, \varepsilon)$

Counting Good Pants and Good Curves

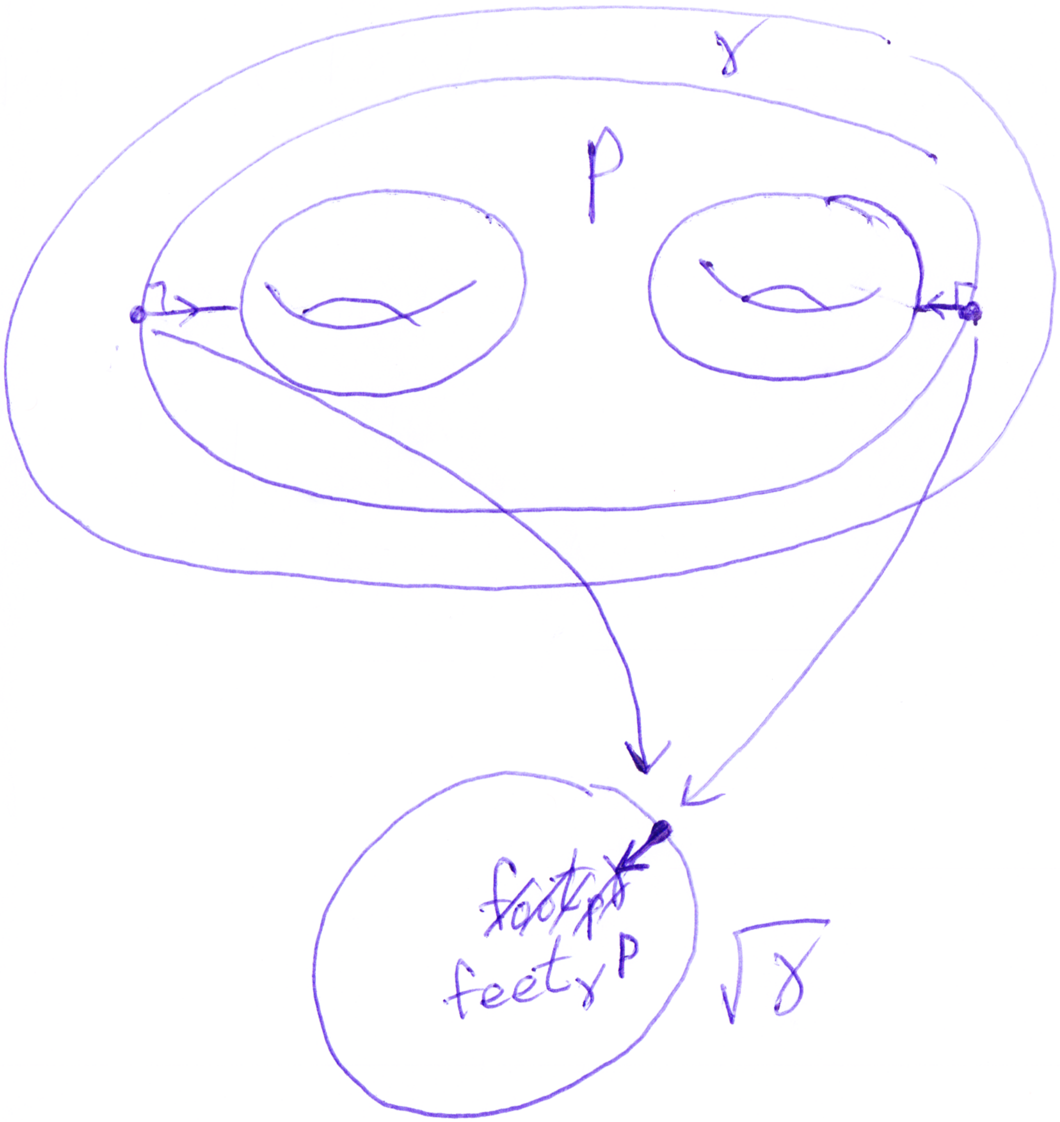
$$\# \Pi_{\varepsilon, R} \asymp e^{3R}$$

$$\# \Gamma_{\varepsilon, R} \asymp e^{2R}/R$$

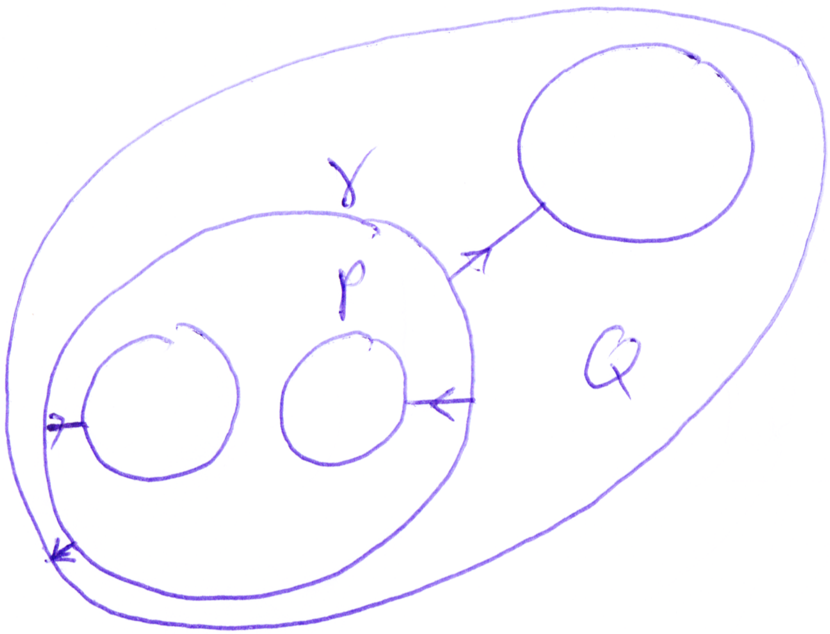
$$\# \{ P \in \Pi_{\varepsilon, R} \mid \gamma \in \partial P \} \asymp R e^{R}$$

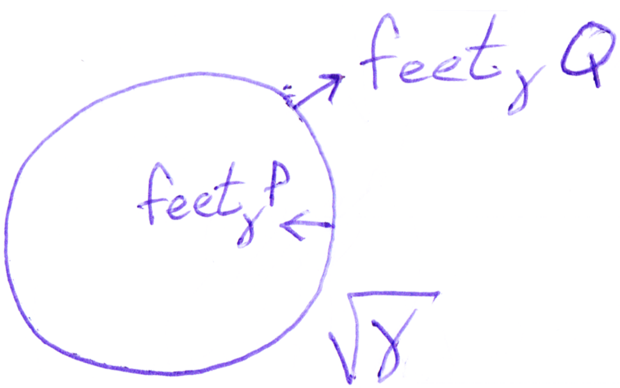
for each $\gamma \in \Gamma_{\varepsilon, R}$

The square root of a geodesic



Shear Coordinates and $N^4(\sqrt{\gamma})$





The Equidistribution Theorem

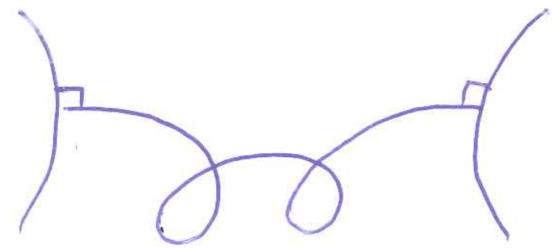
For every good curve γ, ~~and large R,~~

$$\{\text{feet}_\gamma P \mid P \in \Pi_{\varepsilon,R} \text{ and } \gamma \in \partial P\} \subseteq N^1(\sqrt{\gamma})$$

is evenly distributed on $N^1(\sqrt{\gamma})$ to the scale e^{-qR}, for $q = q(S, \varepsilon)$.

(We assume that $R > R_0(S, \varepsilon)$).

Counting Connections Between Geodesics



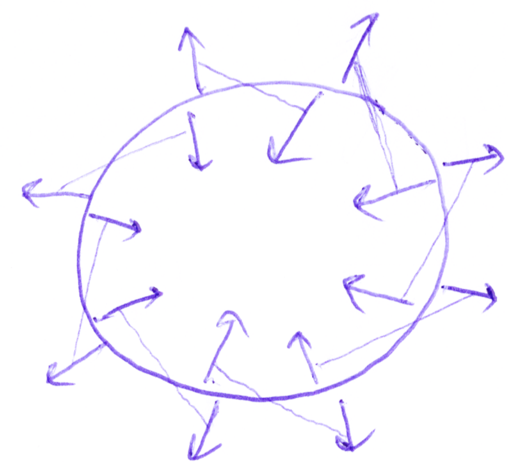
Let A & B be geodesic segments, and take $R_+ > R_- > 0$

Then the number of orthogeodesic connections between A & B with length in $[R_-, R_+]$ is

$$\frac{1}{8\pi|\chi(S)|}\left(e^{R_+} - e^{R_-}\right)|A||B| + O\left(e^{(1-q(S))R_+}\right)$$

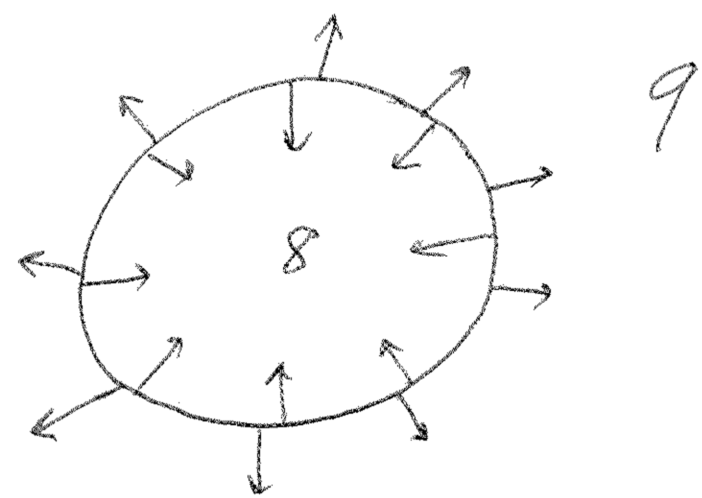
Equidistributed & Balanced $\Rightarrow$ Good Cover

If there were exactly the same number of pants on both sides of each geodesic γ, then we would be ~~all~~ able to assemble the pants in $\Pi_{\epsilon,R}$ to form a good cover of S:



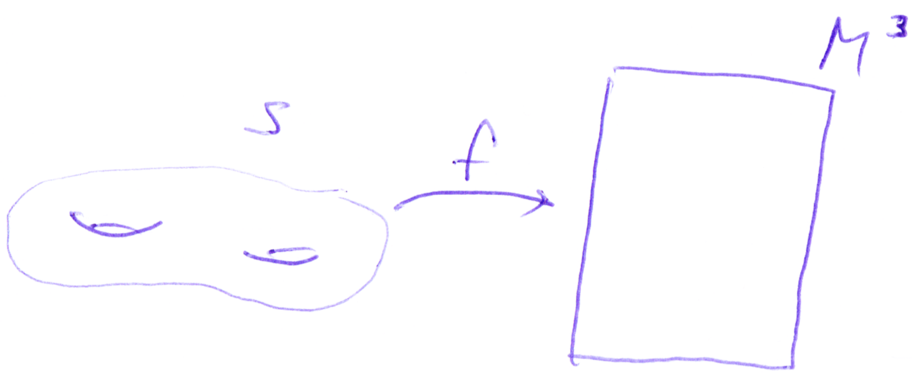
Equidistributed $\Rightarrow$ Nearly balanced

It follows from equidistribution that there are nearly the same number of pants in $\Pi_{\epsilon,R}$ on either side of a good geodesic γ



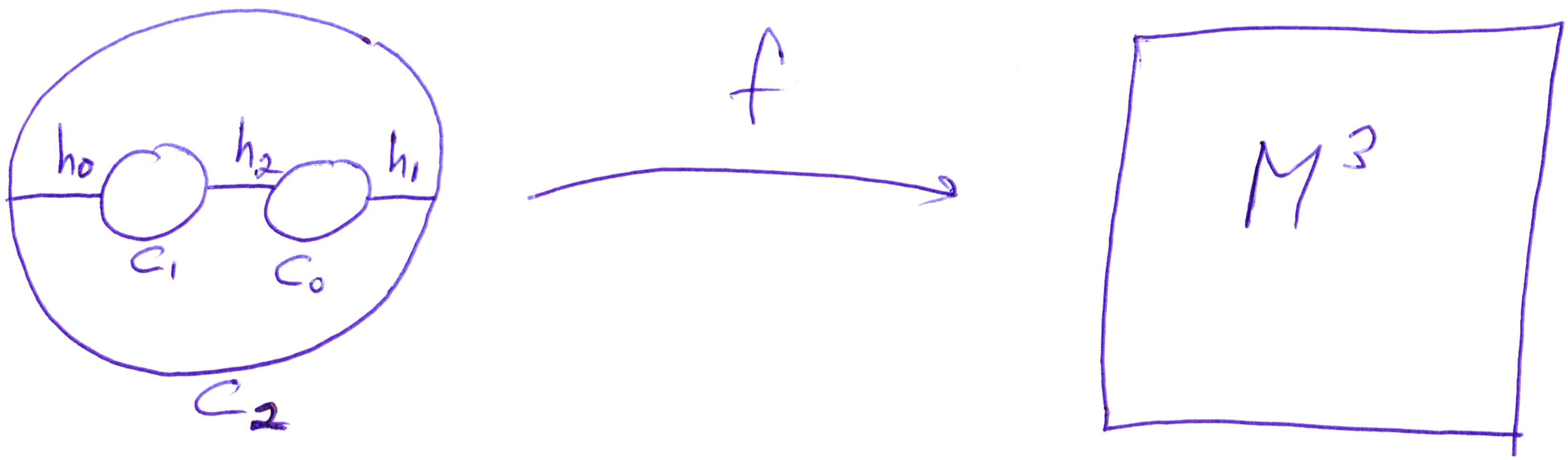
An Interlude in Three Dimensions

In a hyperbolic 3-manifold, $N^1(\gamma)$ (and $N^1(\sqrt{\gamma})$) is connected so we can use the "doubling trick" to build a nearly geodesic immersed surface (which is therefore essential).



$\pi_1(f): \pi_1(S) \to \pi_1(M^3)$ injective

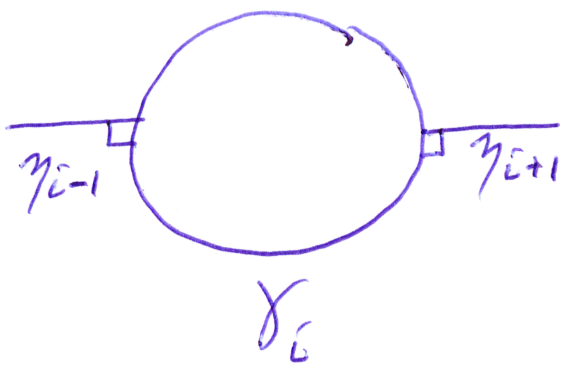
A skew pair of pants

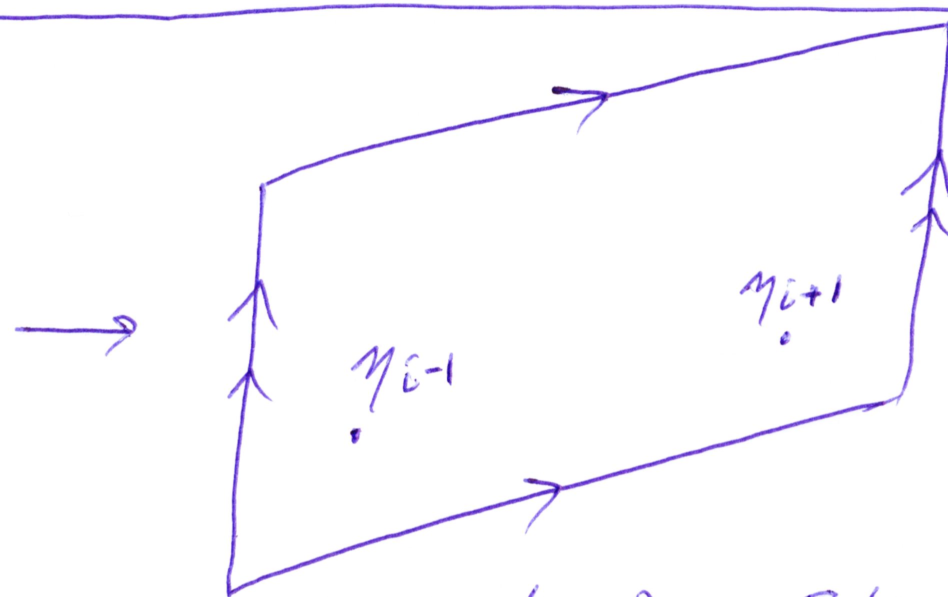


$\gamma_i \equiv f(c_i)$ is a closed geodesic

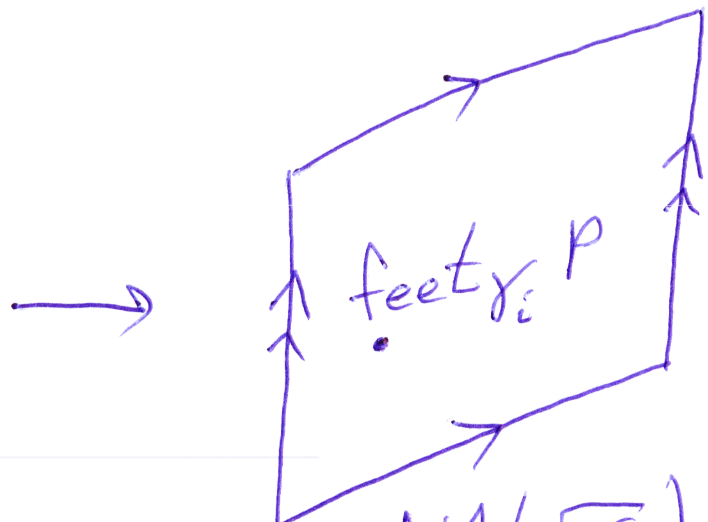
$\eta_i \equiv f(h_i)$ is a geodesic segment orthogonal to $f(\gamma_{i\pm1})$.

The feet of a skew pair of pants





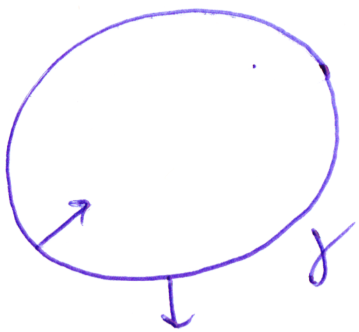
$$N^1(\gamma_i) \cong \mathbb{C}/2\pi i\mathbb{Z} + h\ell(\gamma)\mathbb{Z}$$



$$N^1(\sqrt{\gamma_i})$$

Two and Three Dimensions

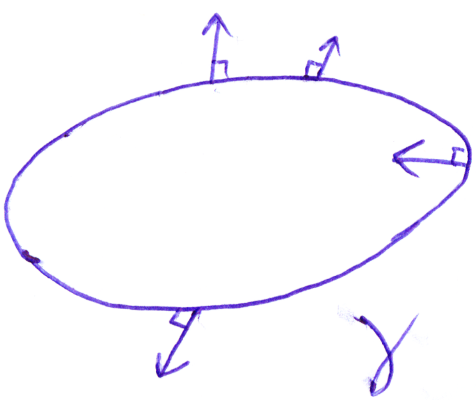
2D



$$N^1(\gamma) \cong \mathbb{R}/_{\ell(\gamma)\cdot\mathbb{Z}} \times \{-1,+1\}$$

$$\cong \mathbb{R}^*/_{\langle x \mapsto e^{\ell(\gamma)}x\rangle}$$

3D



$$N^1(\gamma) \cong \mathbb{C}/_{\ell(\gamma)\cdot\mathbb{Z}+2\pi i\mathbb{Z}}$$

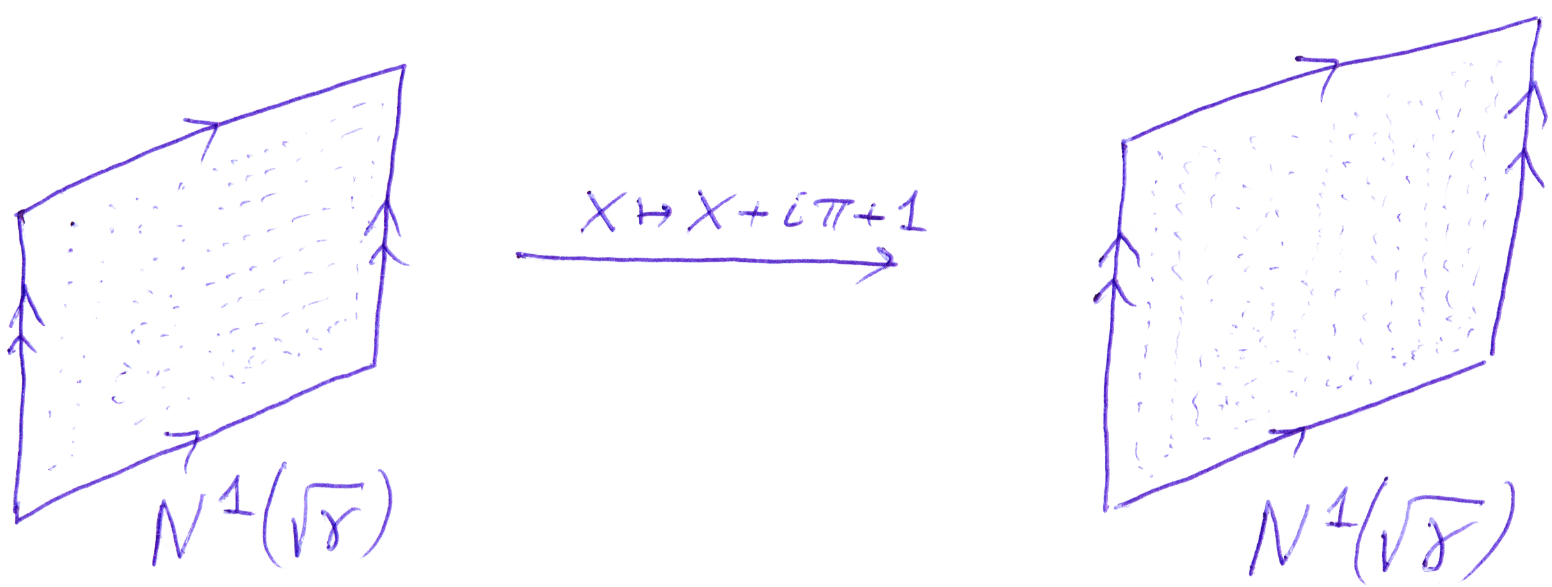
$$\cong \mathbb{C}^*/_{\langle z \mapsto e^{\ell(\gamma)}z\rangle}$$

The meaning of equidistribution

The feet $\left\{ \text{feet}_\gamma P : \begin{array}{l} \gamma \in \partial P \\ P \in \Pi_{\epsilon,R} \end{array} \right\}$

are e^{-qR} - evenly distributed

as points on $N^1(\sqrt{\gamma})$



The "doubling trick" revisited

We take

$$A_\gamma = \{ \mathrm{foot}_\gamma P : \gamma \in \partial P,\ P \in \Pi_{\varepsilon, R} \}$$

We can find

$\sigma : A_\gamma \to A_\gamma$ a permutation

such that $|\sigma(x) - x - i\pi - 1| < \varepsilon/R$
(for all $x \in A_\gamma$)

and then define

$$\begin{tikzcd} \tau : A_\gamma^+ \sqcup A_\gamma^- \arrow[r] & A_\gamma^+ \sqcup A_\gamma^- \end{tikzcd}$$

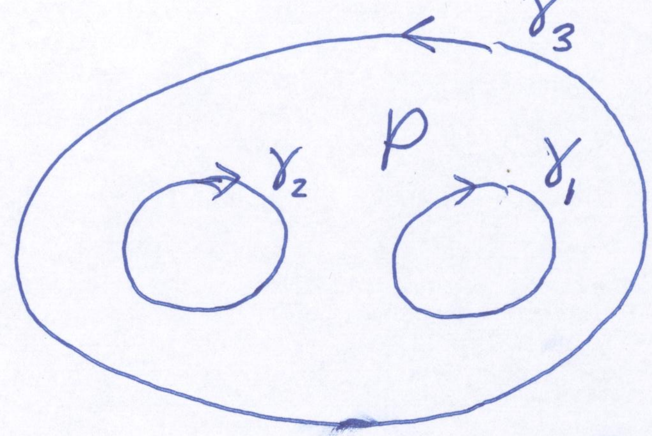
$$A_\gamma^+ \xrightarrow{\sigma} A_\gamma^-, \qquad A_\gamma^- \xrightarrow{\sigma^{-1}} A_\gamma^+$$

The boundary map on sums of good pants

We define

$\partial : \mathbb{Q}\Pi_{\epsilon,R} \to \mathbb{Q}\Gamma_{\epsilon,R}$

by $\partial P = \gamma_1 + \gamma_2 + \gamma_3$.



For $\alpha \in \mathbb{N}\Pi_{\epsilon,R}$,

$\partial\alpha = 0 \Leftrightarrow \alpha$ has the same number of pants on both sides of every γ.

(Note that $\gamma + \gamma^{-1} = 0$ in $\mathbb{Q}\Gamma_{\epsilon,R}$).

The Idea of Self-Correction

We find $g : \mathbb{Q}\Gamma_{\varepsilon,R} \to \mathbb{Q}\Pi_{\varepsilon,R}$ such that

1. $\partial g(\alpha) = \alpha$ whenever $\alpha = \partial \pi$

2. $\|g(\alpha)\|_\infty \leq P(R) e^{-R} \|\alpha\|_\infty$ for all α.

(where $P(R) = CR^N$ is a polynomial in R)

Then let $\Pi = \sum_{P \in \Pi_{\varepsilon,R}} P$, and $\alpha = \partial \Pi$.

Then $\|\alpha\|_\infty \leq e^{(1-q)R}$ by equidistribution

So $\|g(\alpha)\|_\infty \leq P(R) e^{-qR} << 1$.

So $\Pi - g(\alpha)$ is positive and equidistributed

And $\partial(\Pi - g(\alpha)) = \partial\Pi - \partial g(\partial \Pi) = \partial\Pi - \partial\Pi = 0$.

After clearing denominators, we can assemble the pants of $\Pi - g(\alpha)$ to form a good cover!

The Good Pants Homology

We let $H_1^{\varepsilon,R}(S;\mathbb{Q}) = \mathbb{Q}\Gamma_{\varepsilon,R} / \partial\mathbb{Q}\Pi_{\varepsilon,R}$.

We find a series of identities leading to $H_1^{\varepsilon,R}(S;\mathbb{Q}) = H_1(S;\mathbb{Q})$.

The Good Pants Homology

We let $H_1^{\epsilon,R}(S;\mathbb{Q}) = \mathbb{Q}\Gamma_{\epsilon,R} \big/ \partial\mathbb{Q}\Pi_{\epsilon,R}$.

We find a series of identities leading to $H_1^{\epsilon,R}(S;\mathbb{Q}) = H_1(S;\mathbb{Q})$.

Then we observe that $g: \mathbb{Q}\Gamma_{\epsilon,R} \to \mathbb{Q}\Pi_{\epsilon,R}$ has been implicitly defined, such that $\partial g(\alpha) = \alpha$ when $\alpha = 0$ in H_1.

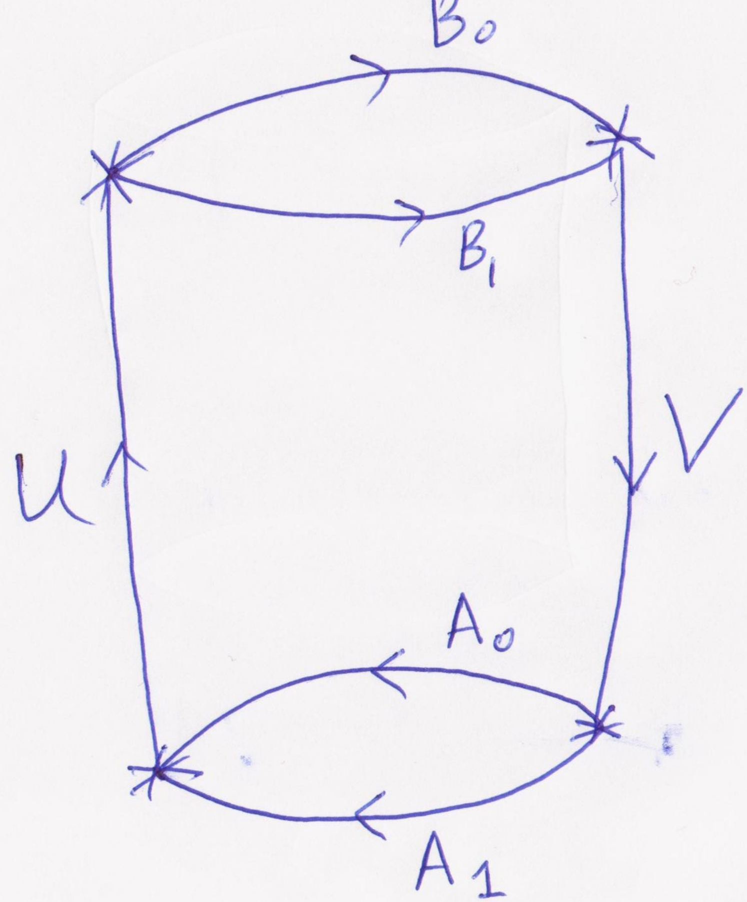
The Algebraic Square Lemma

Under conditions of reasonable geometry,

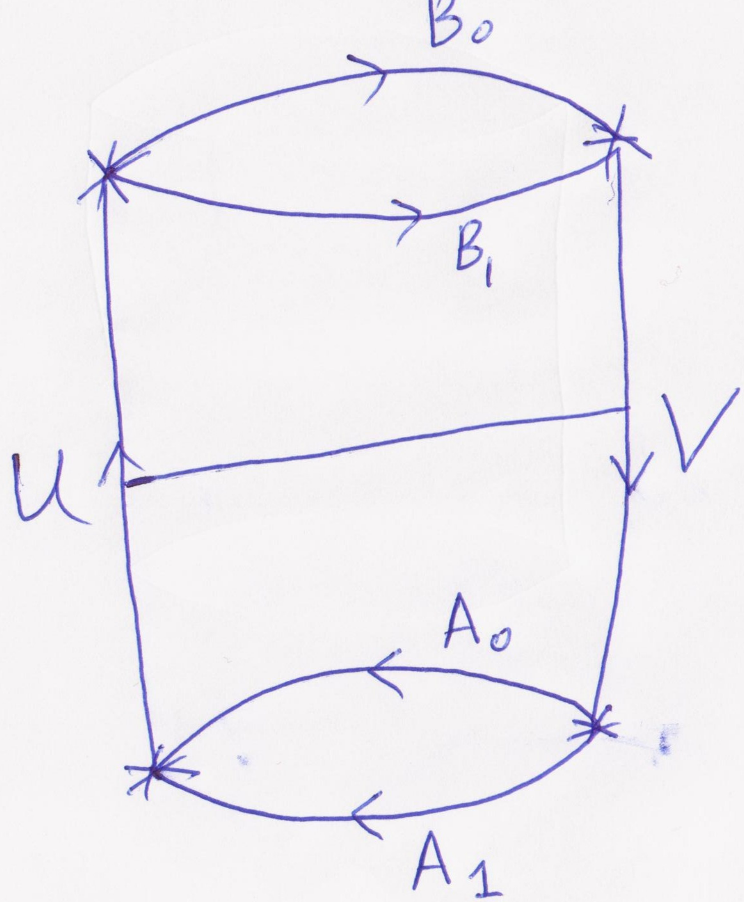
$$\sum_{i,j=0,1} (-1)^{i+j} [A_i U B_j V] \equiv 0$$

in $H_1^{\varepsilon,R}$

(where $[X]$ denotes the closed geodesic freely homotopic to X, for $X \in \pi_1(S,*)$).



$$\sum (-1)^{i+j} [A_i U B_j V]$$



$$\sum (-1)^{i+j} [A_i U B_j V] = \partial \sum (-1)^{i+j} P_{ij}$$

We then define

$$A_T = \frac{1}{2}\left([T A \bar{T} B] - [T \bar{A} T B]\right)$$

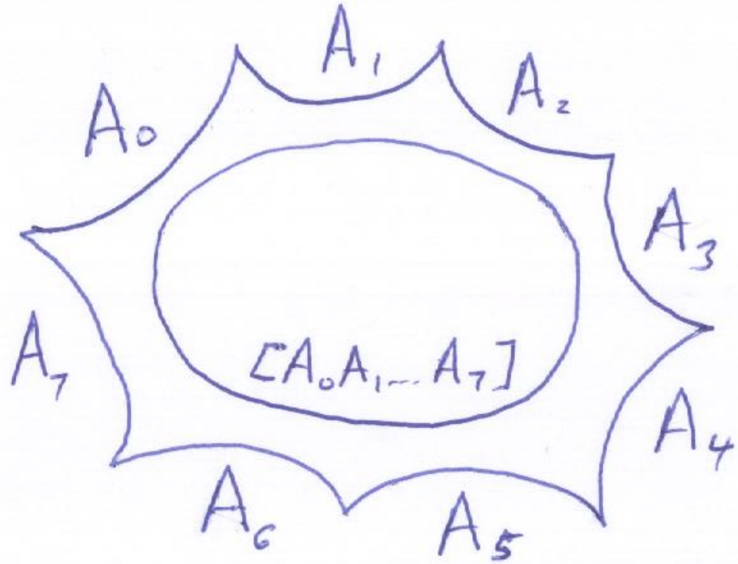
(which is independent of the choice of B in $H_1^{\varepsilon, R}$)

and prove

$$(XY)_T = X_T + Y_T$$

in $H_1^{\varepsilon, R}$.

The Inefficiency of a Closed Piecewise Geodesic



$$I([\cdot A_0 \cdot A_1 \cdot \ldots \cdot A_n \cdot]) = \sum_{i=0}^{n} \ell(\cdot A_i \cdot) - \ell([A_0 \ldots A_n])$$

The Standing Geometric Assumption

T is long

given

bounds on the ~~iff~~ inefficiency.

The ADCB Lemma

$$[T A \bar{T} B T C \bar{T} D] \equiv [T \bar{A} D T C \bar{T} B]$$

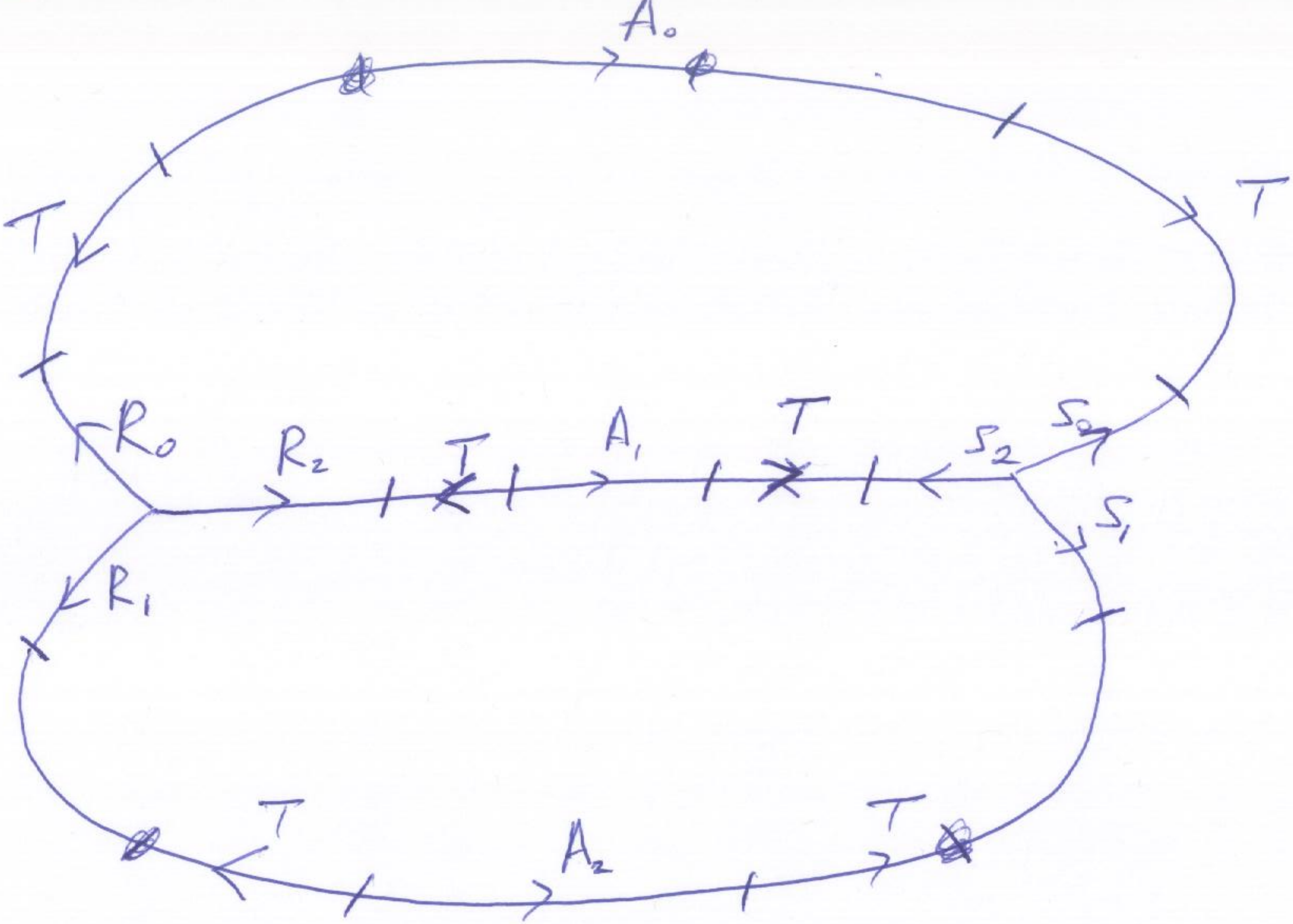
in $H_{\varepsilon, R}$

Four - Part Itenization

$$[T A \bar{T} B T C \bar{T} D] \equiv A_T + B_{\bar{T}} + C_T + D_{\bar{T}}.$$

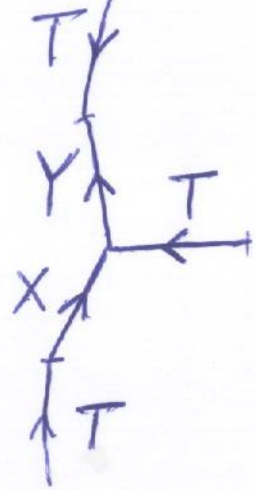
$$\begin{aligned}
[T A \bar{T} B T C \bar{T} D] &\equiv \tfrac{1}{2}\left([T A \bar{T} B T C \bar{T} D] - [\bar{D} T \bar{C} \bar{T} \bar{B} T \bar{A} \bar{T}]\right) \\
&\equiv \tfrac{1}{2}\left([T A \bar{T} B T C \bar{T} D] - [T \bar{A} \bar{T} \bar{D} T \bar{C} \bar{T} \bar{B}]\right) \\
&\equiv \tfrac{1}{2}\left([T A \bar{T} B T C \bar{T} D] - [T \bar{A} \bar{T} \bar{B} T C \bar{T} \bar{D}]\right) \\
&\equiv A_T + B_{\bar{T}} + C_T + D_{\bar{T}}
\end{aligned}$$

The Rotation Lemma



$$\sum (R_i \bar{R}_{i+1})_T + \sum (\bar{S}_{i+1} S_i)_T \equiv 0$$

The XY Lemma



$$(XY)_T = X_T + Y_T$$