

Bachelorarbeit

Topological Entropy of Formal Languages

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Preface

If we have a finite group of matrices, then we can equip it with the rank metric and the normalized Haar measure to obtain a *metric measure space*. Carderi and Thom showed in [?] that the limit of SL_n is *extremely amenable*. The goal of this thesis is to generalize this result to limits of other matrix group families, namely unitary, symplectic, and orthogonal matrices. The general strategy will be the following, given a family $(G_n)_{n \in \mathbb{N}}$ of (mm) matrix groups we first find an upper bound for the *concentration function* of G_n using a consequence of Azemas inequality [?]. As the upper bounds converge to zero we conclude that $(G_n)_{n \in \mathbb{N}}$ is a *Lévy family*, making their limit a *Lévy group*. Finally, we know from [?] that every Lévy group is extremely amenable.

1 Introduction

Define limit of G_n

Examples of matrices in the limit

structure of thesis:

1. Azema
2. Thoms proof (matrices as automorphisms but without form)
3. want to generalize this so we need a form Hence extending the automorphism becomes harder so use Witts lemma
4. generalized version of the proof

2 Martingale Technique

Definition 1. A *martingale* is a family $(f_i, \mathcal{F}_i)_{i \in \{0, \dots, n\}}$ such that

- f_i is integrable for all $i \in \{0, \dots, n\}$,
- f_i is \mathcal{F}_i measurable for all $i \in \{0, \dots, n\}$, and
- $f_i = \mathbb{E}[f_{i+1} | \mathcal{F}_i]$ for all $i \in \{0, \dots, n-1\}$.

Lemma 2. For all $x \in \mathbb{R}$

$$e^x \leq x + e^{x^2}.$$

Lemma 3 (Azema's inequality).

$$\mu(\{x \in X \mid |f(x) - \mathbb{E}(f)| \geq c\}) \leq 2 \exp \left(-\frac{c^2}{4 \sum_{i=1}^n \|d_i\|_\infty^2} \right)$$

$$\mu(\{|f - \mathbb{E}(f)| \geq c\}) \leq 2 \exp \left(-\frac{c^2}{4 \sum_{i=1}^n \|d_i\|_\infty^2} \right)$$

Definition 4. Let (X, d, μ) be an mm-space.

Theorem 5. If an mm-space (X, d, μ) has length l , then the concentration function of X satisfies

$$\alpha_X(\varepsilon) \leq 2 \exp \left(-\frac{\varepsilon^2}{16l^2} \right).$$

Theorem 6. Let G be a compact group with a bi-invariant metric d , and let

$$\{e\} = G_0 < G_1 < \dots < G_n = G$$

be a chain of subgroups. Denote the diameter of G_i / G_{i-1} with respect to the factor metric by a_i . Then the concentration function of the mm-space (G, d, μ) , where μ is the normalized Haar measure, satisfies

$$\alpha_X(\varepsilon) \leq 2 \exp \left(-\frac{\varepsilon^2}{16 \sum_{i=1}^n a_i^2} \right).$$

Theorem 7. The normalized counting measure on the groups $\text{SL}_{2^n}(q)$ concentrates with respect to the rank-metric, i.e. for all $r > 0$

$$\lim_{n \rightarrow \infty} \alpha_{\text{SL}_{2^n}}(r) = 0.$$

Lemma 8. Let (X, d, μ) be an mm-space with diameter d and

$$\Omega_0 = \{X\} \prec \dots \prec \Omega_n = \{\{x\} \mid x \in X\}$$

with a_1, \dots, a_n as in Definition 4. Then

$$\sum_{i=1}^n a_i \geq d.$$

Florian sagt:
"could be that
this only holds
for finite X as
conditions in
definition of
length are just
almost surely"

Proof. Let $x, y \in X$, with $x \neq y$, we show $d(x, y) \leq \sum_{i=1}^n a_i$. Let i_0 be the smallest number such that $[x]_{i_0} \neq [y]_{i_0}$. Since $[x]_0 = X = [y]_0$ we know that i_0 is at least 1. Therefore $[x]_{i_0-1} = [y]_{i_0-1}$ and there is an isomorphism $\varphi_{i_0}: [x]_{i_0} \rightarrow [y]_{i_0}$ such that $d(\varphi_{i_0}(x), y) \leq a_{i_0}$. Let $x_{i_0} = \varphi_{i_0}(x)$, then

$$d(x, y) \leq d(x, x_{i_0}) + d(x_{i_0}, y).$$

Florian sagt:
"here is the a.s.
problem"

If $x_{i_0} = y$, then we are done. Otherwise let i_1 be the smallest number such that $[x_{i_0}]_{i_1} \neq [y]_{i_1}$. Then let $\varphi_{i_1}: [x_{i_0}]_{i_1} \rightarrow [y]_{i_1}$ be an isomorphism such that $d(\varphi_{i_1}(x_{i_0}), y) \leq a_{i_1}$. Define $x_{i_1} = \varphi_{i_1}(x_{i_0})$. Proceeding in this fashion yields elements x_{i_0}, \dots, x_{i_k} such that $x_{i_k} = y$ and

$$d(x, y) \leq d(x, x_{i_0}) + d(x_{i_0}, x_{i_1}) + \dots + d(x_{i_{k-1}}, x_{i_k}) \leq a_{i_0} + \dots + a_{i_k} \leq \sum_{i=1}^n a_i.$$

□

Lemma 9. Let (X, d, μ) be an mm-space with diameter 1 and $\Delta = \min d$. Then the length of X is at least $\Delta^{\frac{1}{2}}$.

Definition 10. The symplectic group of degree $2n$ over a field q , denoted by $\text{Sp}(2n, q)$, is the subgroup of $\text{SL}(2n, q)$ containing all matrices A such that

$$A^T \Omega A = \Omega, \text{ where } \Omega = \begin{pmatrix} 0 & E_n \\ -E_n & 0 \end{pmatrix}.$$

Lemma 11. Let $g: V \rightarrow V$ be an isomorphism, $V = U \oplus U'$, and $g(U') \subseteq U'$. Then the map

$$g': V \rightarrow V$$

$$v \mapsto \begin{cases} g(v) - \pi_{U'}(g(v)) & \text{if } v \notin U' \\ v & \text{if } v \in U' \end{cases}$$

i.e. $g' = \pi_U \circ g - \pi_U \circ g \circ 1_{U'} + 1_{U'}$, is an isomorphism and $d(g, g') \leq \frac{1}{n} \cdot \dim U'$.

Lemma 12. [what we still need (add conditions for ω if necessary)] Let $\omega: V \times V \rightarrow k$ be a bilinear map, U, U' subspaces of V , and $h: U \rightarrow U'$ an isomorphism that preserves ω . Then h can be extended to an isomorphism on V which also preserves ω .

Proof. w.l.o.g. $\dim U + 1 = \dim V$?

□

Lemma 13. Let $V = U \oplus U'$, ω a bilinear map, G be the group of automorphisms of (V, ω) and $G' \leq G$ the subgroup fixing U' . Then the diameter of G/G_i is at most $\frac{3 \cdot \dim U'}{n}$.

Florian sagt:
"...additional
conditions"

Florian sagt:
"adapt this"

Proof. Let $g \in G$, we show that there are $g' \in G$ and $g'' \in G'$ such that $g'(U') \subseteq U'$, $g'|_{U'} = 1_{U'}$, and

$$d(g, g'') \leq d(g, g') + d(g', g'') \leq \frac{2 \dim U'}{n} + \frac{\dim U'}{n}.$$

By Lemma 12 we can extend the map $g^{-1}|_{gU'}$ to a map h' on $V' = \langle U', gU' \rangle$. Now define $g' = (1_{V''} \oplus h')g$, where $V = V'' \oplus V'$ and apply Lemma to g' to obtain g'' .

$$\begin{aligned} \operatorname{im} g - g' &= \operatorname{im} g - (1_{V''} \oplus h')g \\ &= \operatorname{im}(1_{V''} \oplus 1_{V'} - 1_{V''} \oplus h') \\ &= \operatorname{im}(1_{V'} - h') \\ &\subseteq V' \end{aligned}$$

$$d(g, g') = \frac{1}{n} \dim \operatorname{im} g - g' \leq \frac{\dim V'}{n}$$

□

3 Limits of other Matrix group families are Levy groups too

When studying matrices it is often useful to look at the corresponding linear maps of a suitable vector space. In the case of orthogonal, symplectic, or unitary matrices these are linear maps from the vector space to itself preserving an orthogonal, symplectic, or unitary form respectively. Formally, the symplectic group $\text{Sp}_n(q)$ is isomorphic to $\text{Aut}(V, \omega)$, where V is an n -dimensional $F(q)$ vector space and ω is a symplectic form.

As we have to handle only finite dimensional vector spaces here a lot of nice theorems hold. ...

Let V be an n dimensional vector space.

Lemma 14. *For all $U \leq V$ there is an $U' \leq V$ such that $U \oplus U' = V$.*

Let ω be a bilinear form on V .

Lemma 15. *Let $U \leq V$. Then $\dim U^\perp = \dim V - \dim U$.*

Lemma 16. *Let $U \leq V$. Then $U^{\perp\perp} = U$.*

Lemma 17. *There exists a $U \leq V$ with $\dim U \leq 2$ such that $V = U \oplus U^\perp$.*

Proof. Let $e \in V \setminus \{0\}$. By Lemma 15 $\dim e^\perp = n - 1$.

If $e \notin e^\perp$, then $V = \langle e \rangle \oplus e^\perp$ and $\langle e \rangle$ is the desired U .

If $e \in e^\perp$, then extend e to a basis e, b_2, \dots, b_{n-1} of e^\perp and consider the 2-dimensional subspace $U := \langle b_2, \dots, b_{n-1} \rangle^\perp$. Now we have to show that

$$U \cap U^\perp = 0.$$

Take v from the intersection. By Lemma 16 $U^\perp = \langle b_2, \dots, b_{n-1} \rangle$ and $v \perp b_i$ for all $i \in \{2, \dots, n-1\}$. Since $\langle b_2, \dots, b_{n-1} \rangle \leq e^\perp$ we also have $v \perp e$. Hence $v \in e^{\perp\perp} = \langle e \rangle$ and $v = \lambda e$. Now $e \notin \langle b_2, \dots, b_{n-1} \rangle$ implies $v = 0$. Henceforth $V = U \oplus U^\perp$. \square

Lemma 18. *Let $U \leq V$ and $f: V \rightarrow V$ be an isometry such that $f|_U = 1_U$. Then $f(U^\perp) = U^\perp$.*

Proof. As $\dim f(U^\perp) = \dim U^\perp$ it suffices to show that $f(u') \perp u$ for all $u \in U$ and $u' \in U^\perp$.

$$\begin{aligned} \omega(f(u'), u) &= \omega(f(u'), f(u)) \\ &= \omega(u', u) \\ &= 0 \end{aligned}$$

This concludes the proof. \square

Lemma 19. *For all $W \leq V$ there is a $W' \leq W^\perp$ such that $W \cap W' = 0$ and*

$$\dim W' \geq \dim V - 2 \dim W.$$

Proof. By Lemma 14 there is a W' such that

$$W^\perp = (W^\perp \cap W) \oplus W'.$$

Clearly, $W \cap W' = 0$ and

$$\dim W' = \dim W^\perp - \dim(W^\perp \cap W) \geq \dim W^\perp - \dim W.$$

Whats left is to show that $\dim W^\perp \geq \dim V - \dim W$. Let $b_1, \dots, b_{\dim W}$ be a basis of W . Then W^\perp is equal to the kernel of the linear map

$$V \rightarrow F_q^{\dim W} \quad v \mapsto \begin{pmatrix} \omega(b_1, v) \\ \vdots \\ \omega(b_{\dim W}, v) \end{pmatrix}.$$

Now the statement follows from the rank-nullity theorem. \square

Lemma 20. *Let $U, W \leq V$ such that $U \perp W$ and $U \cap W = 0$. Then $\langle U, W \rangle \cong U \oplus W$.*

Lemma 21. *Let $g_1: U_1 \rightarrow W_1$ and $g_2: U_2 \rightarrow W_2$ be isometries such that $U_1 \perp U_2$, $U_1 \cap U_2 = 0$, $W_1 \perp W_2$, and $W_1 \cap W_2 = 0$. Then $g_1 \oplus g_2: U_1 \oplus U_2 \rightarrow W_1 \oplus W_2$ is also an isometry.*

Florian sagt:
"maybe $g: U_1 \rightarrow U_2$ and $h: W_1 \rightarrow W_2$ better"

Proof. Obviously, $g_1 \oplus g_2$ is again a bijective linear map. Consider $v_1 + v_2, u_1 + u_2 \in U_1 \oplus U_2$

$$\begin{aligned} \omega(v_1 + v_2, u_1 + u_2) &= \omega(v_1, u_1) + \omega(v_1, u_2) + \omega(v_2, u_1) + \omega(v_2, u_2) \\ &= \omega(v_1, u_1) + 0 + 0 + \omega(v_2, u_2) && (U_1 \perp U_2) \\ &= \omega(g_1(v_1), g_1(u_1)) + \omega(g_2(v_2), g_2(u_2)) \\ &= \omega(g_1(v_1), g_1(u_1)) + \omega(g_1(v_1), g_2(u_2)) \\ &\quad + \omega(g_2(v_2), g_1(u_1)) + \omega(g_2(v_2), g_2(u_2)) && (W_1 \perp W_2) \\ &= \omega(g_1 \oplus g_2(v_1 + v_2), g_1 \oplus g_2(u_1 + u_2)) \end{aligned}$$

Hence $g_1 \oplus g_2$ preserves ω . \square

[other useful theorems]

Theorem 22 (Witt). *Let V be an orthogonal, symplectic, or unitary space. Let U and W be subspaces of V and suppose $\alpha: U \rightarrow W$ is an isometry. Then α extends to an isometry of V .*

Lemma 23. *Let G be an orthogonal, symplectic, or unitary group. ...*

Proof. $G = \text{Aut}(V, \omega)$ for some vector space V with bilinear form ω . Use Lemma 17 to obtain $U \leq V$ such that $V = U \oplus U^\perp$ and $\dim U \leq 2$. Define $H = \text{Aut}(U^\perp, \omega)$. Our aim is to find for any $g \in G$ an $g' \in H$ such that $d(g, g') \leq \frac{8}{n}$.

The idea is to find a map $h \in H$ that behaves like the inverse of g on gU and like the identity on most of the rest. Then hg is the desired g' .

Let $g \in G$ and define $W = \langle U, gU \rangle$. By Lemma 19 there is a W' such that $\dim W' \geq n - 8$, $W' \leq W^\perp$, and $W' \cap W = 0$. Consider the map

$$g^{-1}|_{gU} \oplus 1_{W'}: gU \oplus W' \rightarrow U \oplus W'$$

as $g^{-1}|_{gU}$ and $1_{W'}$ are isometries and $W \perp W'$ Lemma 21 implies that the above map is also an isometry. By Witt's lemma this isometry can be extended to an isometry $h: V \rightarrow V$.

$$\begin{aligned} n \cdot d(g, hg) &= \dim \operatorname{im}(g - hg) \\ &\leq 8 + \dim \operatorname{im}(g - hg)|_{W'} && (\dim W' \geq n - 8) \\ &= 8 + \dim \operatorname{im}(g - g)|_{W'} && (h|_{W'} = 1_{W'}) \\ &= 8 \end{aligned}$$

Finally, we need to show that $hg \in H$, here the choice of H using Lemma 17 comes into play. By construction of h we have that $hg|_U = 1_U$. Therefore we can apply Lemma 18 and get that $hg(U^\perp) = U^\perp$. Hence $hg \in H$ and $d(g, hg) \leq \frac{8}{n}$. \square

4 Fun

Consider an n -dimensional cube with 2^k nodes on each edge. Then its diameter $\nabla_{n,k}$ and length $L_{n,k}$ are

$$\nabla_{n,k} = \sqrt{(2^k - 1) \cdot n} \qquad L_{n,k} = \sqrt{\sum_{i=0}^{k-1} 2^{2i} \cdot n}.$$

Henceforth

$$\lim_{n \rightarrow \infty} \frac{L_{n,k}}{\nabla_{n,k}} = \frac{L_{1,k}}{\nabla_{1,k}} \qquad \text{and} \qquad \lim_{k \rightarrow \infty} \frac{L_{n,k}}{\nabla_{n,k}} = \frac{1}{\sqrt{3}}.$$

ERKLÄRUNG

Hiermit erkläre ich, dass ich die am heutigen Tag eingereichte Diplomarbeit zum Thema “Topological Entropy of Formal Languages” selbstständig erarbeitet, verfasst und Zitate kenntlich gemacht habe. Andere als die angegebenen Hilfsmittel wurden von mir nicht benutzt.

Datum

Unterschrift