

Bachelorarbeit

**Topological Entropy of
Formal Languages**

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Contents

1	Martingale Technique	2
2	Limits of other Matrix group families are Levy groups too	5
3	Fun	6

1 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'' .

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

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

□

2 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 $\mathrm{Sp}_n(q)$ is isomorphic to $\mathrm{Aut}(V, \omega)$, where V is an n -dimensional $F(q)$ vector space and ω is a symplectic form.

As we have to only handle 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. *For all $W \leq V$ there is a $W' \leq W^\perp$ such that $W \cap W' = \emptyset$ 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, $W \cap W' = \emptyset$ 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 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. □

[other useful theorems]

Theorem 16 (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 17. *Let G be an orthogonal, symplectic, or unitary group.*

Proof. $G = \mathrm{Aut}(V, \omega)$ for some vector space V with bilinear form ω . Let $\{e_1, \dots, e_n\}$ be a basis of V and $H = \mathrm{Aut}(\langle e_1, \dots, e_n \rangle, \omega)$. Our aim is to find for any $g \in G$ an $h \in H$ such that $d(g, h) \leq \frac{4}{n}$.

Let $g \in G$ □

3 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