

Bachelorarbeit

**Measure Concentration for
Symplectic Groups**

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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*. There is a well defined limit of ... 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
5. application coloring theorem

2 Limits of matrix groups and extreme amenability

Let $GL_n(q)$ be the general linear group over the q element field \mathbb{F}_q and let G be a subgroup of $GL_n(q)$. We can equip G with the (normalized) *rank-metric* $d(g, h) := \frac{1}{n} r(g - h)$. Since all matrices in G have full rank, this metric is bi-invariant, i.e. $d(kg, kh) = d(g, h) = d(gk, hk)$ for all $g, h, k \in G$. Let $G_n \leq GL_{2^n}(q)$ be a family of subgroups, such that $\begin{pmatrix} g & 0 \\ 0 & g \end{pmatrix} \in G_{n+1}$ for all $g \in G_n$. Note that the map

$$\varphi_n: G_n \mapsto G_{n+1}, \text{ where } \varphi_n(g) = \begin{pmatrix} g & 0 \\ 0 & g \end{pmatrix}$$

is an isometric homomorphism for all $n \in \mathbb{N}$. Hence we can define the inductive limit of $(G_n)_{n \in \mathbb{N}}$. We denote the metric completion of this limit by $\text{clim}_{n \rightarrow \infty} G_n$.

Lemma 1. *The group $\text{clim}_{n \rightarrow \infty} G_n$ is a topological group.*

Proof. The bi-invariance of d is preserved by the limit and the completion. ... \square

Now that we have a topology on $G := \text{clim}_{n \rightarrow \infty} G_n$ we can ask whether it is *extremely amenable*, i.e. every continuous action of G on a compact topological space admits a fixed point. It is hard to show this directly, but we know that every Lévy group is extremely amenable. Hence we will show that for suitable $(G_n)_{n \in \mathbb{N}}$ the limit G will be a Lévy group.

Before we can define Lévy groups we need the following definition.

Definition 2. A *metric measure space* (mm-space) X is a triple (X, d, μ) , where d is a metric on the set X and μ is a measure on the Borel σ -algebra induced by d . We will always assume that $\mu(X) = 1$. For any set $A \subseteq X$ denote the r -neighborhood of A , i.e. $\{x \in X \mid \exists y \in A. d(x, y) < r\}$, by $N_r(A)$. The *measure concentration function* of X is defined as

$$\alpha_X(r) = \sup\{1 - \mu(N_r(A)) \mid A \subseteq X, \mu(A) \geq \frac{1}{2}\}.$$

A family of mm-spaces X_n with diameter 1 is called a *Lévy family* if

$$\alpha_{X_n}(r) \rightarrow 0$$

for all $r > 0$.

A topological space X is a *Polish space* if it is homeomorphic to a complete metric space that has a countable dense subset.

Now we can come back to groups.

Definition 3. A *Polish group* G is a topological group where the underlying topological space is a Polish space. A *Lévy group* is a group G equipped with a metric d , where

- G with the topology induced by d is a Polish group and
- there is a sequence $(G_n)_{n \in \mathbb{N}}$ of compact subgroups, such that $(G_n, d|_{G_n}, \mu_n)_{n \in \mathbb{N}}$ is a Lévy family. Here μ_n is the normalized Haar measure of G_n .

Note that the normalized Haar measure of G_n is just the normalized counting measure. The following theorem from [?] gives the desired connection to extreme amenability.

Theorem 4. *Every Lévy group is extremely amenable.*

To apply this theorem to our setting we need the following lemma.

Lemma 5. *Let $G_n \leq \text{GL}_{2^n}(q)$ and $G = \text{clim}_{n \rightarrow \infty} G_n$. Then G is a Polish group.*

Proof. By Lemma 1 G is already a topological group and by definition it is also a complete metric space. Furthermore, every G_n is finite. Hence the inductive limit of the G_n is a countable dense subset of G . \square

Whether G is also a Lévy group depends on the particular choice of $(G_n)_{n \in \mathbb{N}}$. To show that for certain sequences G will be a Lévy group, we will bound $\alpha_{G_n}(r)$. The next section develops the methods necessary to obtain this upper bound.

Florian sagt:
"definition ugly,
use d_A ?"

Florian sagt:
"lim G_n dense
in G ?"

3 An upper bound for the measure concentration function

In this section we will prove Azema's inequality and as a consequence, we will obtain an upper bound for the measure concentration function. As the next results rely heavily on stochastic methods we will briefly introduce the necessary notions. Since the G_n are all finite and equipped with the normalized counting measure we will only consider *probability spaces* (X, Σ, μ) , where X is finite, Σ is a σ -algebra over X , and $\mu(A) = |A|/|X|$ for $A \subseteq X$. For a more general approach see [?]. Note that Σ has a very nice representation.

Lemma 6. *Let Σ be a σ -algebra over a finite set X , then Σ is the smallest σ -algebra containing the partition A_1, \dots, A_n , where the A_i 's are the minimal nonempty sets in Σ .*

Proof. First we show that A_1, \dots, A_n is a partition of X . Since $A_i \cap A_j \in \Sigma$ we conclude, by minimality of A_i and A_j , that either $i = j$ or $A_i \cap A_j = \emptyset$. Clearly, every element of X is contained in a one of the A_i .

For $A \in \Sigma$ we have, again by minimality, that $A \cap A_i$ is either A_i or \emptyset . Therefore A can be written as a union of A_i 's. \square

Note that it follows from the proof that any $A \in \Sigma$ can be written as $\bigcup_{i \in I} A_i$ for a suitable I . This lemma allows us to use partitions and σ -algebras interchangeably. We will denote the partition corresponding to Σ by A_1, \dots, A_n , for Σ' we will use $A'_1, \dots, A'_{n'}$, etc. The next definition is simplified a lot by only considering finite X .

Definition 7. Let (X, Σ, μ) be a probability space, $f: X \rightarrow \mathbb{R}$ be a measurable function, and Σ' be a sub- σ -algebra of Σ . Then the *conditional expectation* of f with respect to Σ' is defined as

$$\mathbb{E}(f \mid \Sigma') := \sum_{i=1}^{n'} \mathbb{E}(f \mid A'_i) \cdot \mathbb{1}_{A'_i}.$$

One often thinks of Σ' as the available information, a finer partition means more information. The conditional expectation $\mathbb{E}(f \mid \Sigma')$ is the best approximation of f given only the information from Σ' . With this intuition the statements from the following lemma are not surprising.

Lemma 8. *Let (X, Σ, μ) be a probability space, $f, g: X \rightarrow \mathbb{R}$ be measurable functions, $\Sigma'' \subseteq \Sigma' \subseteq \Sigma$ be sub- σ -algebras. Then*

- i) *if $f \leq g$, then $\mathbb{E}(f \mid \Sigma') \leq \mathbb{E}(g \mid \Sigma')$,*
- ii) *for any Σ' -measurable function $h: X \rightarrow \mathbb{R}$ we have $\mathbb{E}(hf \mid \Sigma') = h \cdot \mathbb{E}(f \mid \Sigma')$,*
- iii) *also $\mathbb{E}(\mathbb{E}(f \mid \Sigma') \mid \Sigma'') = \mathbb{E}(f \mid \Sigma'') = \mathbb{E}(\mathbb{E}(f \mid \Sigma'') \mid \Sigma')$.*

Proof. To i): If $f \leq g$, then

$$\mathbb{E}(f \mid \Sigma') = \sum_{i=1}^n \mathbb{E}(f \mid A'_i) \cdot \mathbb{1}_{A'_i} \leq \sum_{i=1}^n \mathbb{E}(g \mid A'_i) \cdot \mathbb{1}_{A'_i} = \mathbb{E}(g \mid \Sigma').$$

To ii): Let $h: X \rightarrow \mathbb{R}$ be Σ' -measurable function, then $h = \sum_{i=1}^{n'} h_i \mathbb{1}_{A'_i}$. Now

$$\begin{aligned} \mathbb{E}(hf \mid \Sigma') &= \sum_{i=1}^{n'} \mathbb{E}(hf \mid A'_i) \mathbb{1}_{A'_i} \\ &= \sum_{i=1}^{n'} h_i \mathbb{E}(f \mid A'_i) \mathbb{1}_{A'_i} \\ &= h \cdot \mathbb{E}(f \mid \Sigma'). \end{aligned}$$

To iii): Note that $\mathbb{E}(\mathbb{E}(f \mid \Sigma') \mid A'') = \mathbb{E}(f \mid A'')$ for all $A'' \in \Sigma''$.

$$\begin{aligned} \mathbb{E}(\mathbb{E}(f \mid \Sigma') \mid \Sigma'') &= \sum_{i=1}^{n''} \mathbb{E}(\mathbb{E}(f \mid \Sigma') \mid A''_i) \cdot \mathbb{1}_{A''_i} \\ &= \sum_{i=1}^{n''} \mathbb{E}(f \mid A''_i) \cdot \mathbb{1}_{A''_i} \quad (A''_i \in \Sigma') \\ &= \mathbb{E}(f \mid \Sigma'') \\ &= \sum_{j=1}^{n''} \mathbb{E}(f \mid A''_j) \cdot \mathbb{1}_{A''_j} \cdot \sum_{i=1}^{n'} \mathbb{1}_{A'_i} \\ &= \sum_{i=1}^{n'} \sum_{j=1}^{n''} \mathbb{E}(\mathbb{E}(f \mid A''_j) \mid A'_i) \cdot \mathbb{1}_{A''_j} \cdot \mathbb{1}_{A'_i} \\ &= \sum_{i=1}^{n'} \sum_{j=1}^{n''} \mathbb{E}(\mathbb{E}(f \mid A''_j) \cdot \mathbb{1}_{A''_j} \mid A'_i) \cdot \mathbb{1}_{A'_i} \quad (\text{by ii}) \\ &= \mathbb{E}(\mathbb{E}(f \mid \Sigma'') \mid \Sigma') \end{aligned}$$

This concludes the proof. \square

The following lemma might not seem very interesting, but changing the exponent from x to x^2 is the very foundation for Azema's inequality.

Lemma 9. For all $x \in \mathbb{R}$

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

Proof. Note that for $x = 0$ both sides are equal to 1. As both sides are differentiable it suffices to show that the derivative of the right hand side is larger than the derivative of the left hand side for all $x \geq 0$ and smaller for all $x \leq 0$. Hence, we want to show

$$e^x \geq 1 + 2xe^{x^2} \text{ for all } x \leq 0 \quad \text{and} \quad e^x \leq 1 + 2xe^{x^2} \text{ for all } x \geq 0.$$

As for $x = 0$ both sides are again equal to 1 we can reduce the problem, by similar reasoning, to the question whether

$$e^x \leq 2e^{x^2} + 4x^2e^{x^2} \text{ for all } x \in \mathbb{R}.$$

- For $x = 0$ the terms reduce to $1 \leq 2$.
- For $x < 0$ the left hand side is bounded by 1, while the right hand side is still larger than 2.
- For $1 \leq x$ we have $x \leq x^2$ and the inequality holds trivially.
- For $0 < x < 1$ note that the both sides are increasing. Hence the inequality holds for all x with $e^x \leq 2$. Finally, $\ln 2 \geq \frac{1}{2}$ and therefore the right hand side with $x = \ln 2$ evaluates to a number larger than e .

□

Before we will prove Azema's inequality let us introduce some useful notation. Whenever there is no danger of confusion we will abbreviate sets of the form

$$\{x \in X \mid \text{Condition}(x) \text{ holds}\} \quad \text{by} \quad \{\text{Condition}\}.$$

For example $\{x \in X \mid f(x) = c\}$ becomes $\{f = c\}$.

Lemma 10 (Azema's inequality). *Let (X, Σ, μ) be a probability space, $f: X \rightarrow \mathbb{R}$ a measurable function, and $\{X\} = \Sigma_0 \subseteq \dots \subseteq \Sigma_n = \Sigma$ a chain of sub- σ -algebras. Define $f_i := \mathbb{E}(f \mid \Sigma_i)$ and $d_i := f_i - f_{i-1}$. Then for every $c \geq 0$*

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

Note that $(f_i, \Sigma_i)_{0 \leq i \leq n}$ is a discrete martingale.

Proof. First, observe that $f_0 = \mathbb{E}(f \mid \{X\}) = \mathbb{E}(f)$ and $f_n = \mathbb{E}(f \mid \Sigma) = f$. Using

a simple telescoping sum we obtain $f - \mathbb{E}(f) = d_1 + \dots + d_n$. Therefore

$$\begin{aligned}
\mu(\{f - \mathbb{E}(f) \geq c\}) &= \mu(\{\sum_{i=1}^n d_i \geq c\}) \\
&= \mu(\{\lambda \cdot \sum_{i=1}^n d_i \geq \lambda c\}) && (\text{for } \lambda > 0) \\
&= \mu(\{e^{\lambda \cdot \sum_{i=1}^n d_i - \lambda c} \geq 1\}) \\
&\leq \mathbb{E}(e^{\lambda \cdot \sum_{i=1}^n d_i}) \cdot e^{-\lambda c} && (*) \\
&= \mathbb{E}(e^{\lambda d_1} \cdot \dots \cdot e^{\lambda d_{n-1}} \cdot \mathbb{E}(e^{\lambda d_n} \mid \Sigma_{n-1})) \cdot e^{-\lambda c} && (\text{Lemma 8}) \\
&\leq \mathbb{E}(e^{\lambda d_1} \cdot \dots \cdot e^{\lambda d_{n-1}}) \cdot e^{\lambda^2 \cdot \|d_n\|_\infty^2} \cdot e^{-\lambda c} && (**) \\
&\vdots \\
&\leq e^{\lambda^2 \cdot \|d_1\|_\infty^2} \cdot \dots \cdot e^{\lambda^2 \cdot \|d_{n-1}\|_\infty^2} \cdot e^{\lambda^2 \cdot \|d_n\|_\infty^2} \cdot e^{-\lambda c} \\
&= e^{\lambda^2 \cdot \sum_{i=1}^n \|d_i\|_\infty^2 - \lambda c}.
\end{aligned}$$

For (*) note that for any measurable function $g: X \rightarrow \mathbb{R}$ with $g \geq 0$ we have

$$\mu(\{g \geq 1\}) = \mathbb{E}(\mathbb{1}_{\{g \geq 1\}}) \leq \mathbb{E}(g).$$

For (**) we need to use Lemma 9

$$\begin{aligned}
\mathbb{E}(e^{\lambda d_i} \mid \Sigma_{i-1}) &\leq \mathbb{E}(\lambda d_i \mid \Sigma_{i-1}) + \mathbb{E}(e^{\lambda^2 d_i^2} \mid \Sigma_{i-1}) \\
&= \lambda \cdot \mathbb{E}(f_i - f_{i-1} \mid \Sigma_{i-1}) + \mathbb{E}(e^{\lambda^2 d_i^2} \mid \Sigma_{i-1}) \\
&\leq 0 + e^{\lambda^2 \|d_i\|_\infty^2}.
\end{aligned} \tag{Lemma 8}$$

Substituting $-\frac{c^2}{\sum_{i=1}^n \|d_i\|_\infty^2}$ for λ we conclude that

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

The same calculations with $-d_i$ instead of d_i yield the dual inequality

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

These two statements obviously give us the desired result. \square

The next goal is to connect Azema's inequality with the measure concentration function. To achieve this we first need to introduce a new property of mm-spaces.

Definition 11. Let $X = (X, d, \mu)$ be an mm-space. The *length* of X is the infimum over all l with the following property. There is a refining sequence of partitions

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

where for every $i \in \{1, \dots, n\}$ there is an a_i such that $\sum_{i=1}^n a_i^2 = l^2$ and for every $A \in \Omega_{i-1}$, $x, y \in A$ there is an isomorphism (of metric spaces) $\phi: [x]_i \rightarrow [y]_i$ with

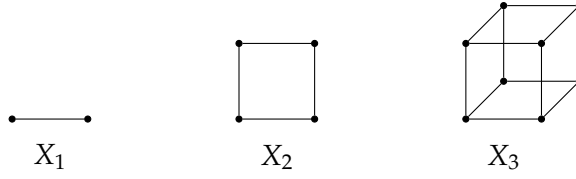
$$d(z, \phi(z)) \leq a_i \text{ for all } z \in [x]_i.$$

Note that since μ is the counting measure ϕ is also an isomorphism of mm-spaces. As this definition is quite hard we will look at some properties and examples of the length of X before proceeding.

Lemma 12. *Let X be an mm-space. Then the length of X is at most the diameter of X .*

Proof. Consider only the two partitions $\{X\} \prec \{\{x\} \mid x \in X\}$. \square

Example 13. Let us look at the n -dimensional cube $X_n = \{0, 1\}^n$.



We will only consider the following sequence of partitions

$$\Omega_0 \prec \dots \prec \Omega_n \text{ with } \Omega_i = \{wX_{n-i} \mid w \in \{0, 1\}^i\}.$$

First, we equip X_n with the euclidean metric and rescale it such that the diameter is 1. To bound the length of the resulting space X_n^E consider $[x]_i \neq [y]_i$. Note that x and y are w.l.o.g. of the form $w0u$ and $w1v$ for some $w \in \{0, 1\}^{i-1}$, $u, v \in \{0, 1\}^{n-i}$. The isomorphism ϕ takes an element $w0u'$ in $[x]_i$ and maps it to $w1u'$. The length of a side in X_n^E is $\frac{1}{\sqrt{n}}$, hence every a_i is $\frac{1}{\sqrt{n}}$ and the length of X_n^E is bounded by $\sum_{i=1}^n \frac{1}{\sqrt{n}} = 1$.

Secondly, we use the hemming metric and obtain the mm-space X_n^H with diameter 1. It has side length $\frac{1}{n}$ and therefore the length of X_n^H is bounded by $\sum_{i=1}^n \frac{1}{n^2} = \frac{1}{n}$. We see that here the length of X_n^H converges to 0 as n tends to infinity. We will show that this means that the measure concentration function $\alpha_{X_n^H}(r)$ also goes to 0 for any fixed $r > 0$.

Between any two points in X there is almost surely a path x_0, \dots, x_n such that

$$\sum_{i=1}^n d(x_{i-1}, x_i)^2 \leq \text{len}(X)^2$$

(this path probably has some special properties).

Theorem 14. *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 15. Let G be a compact group with a bi-invariant metric d , and let

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

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

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

Lemma 17. Let (X, d, μ) be an mm-space with diameter d and

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

with a_1, \dots, a_n as in Definition 11. Then

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

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

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

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

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

□

Lemma 18. Why is this not the case? (it contradicts the main theorem)

$$\frac{1}{\sqrt{3}} \mathrm{diam}(X) \leq \mathrm{len}(X) \leq \mathrm{diam}(X)$$

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

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

Lemma 19. 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 20. 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 21. 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 22. [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 23. 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 22 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'' .

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

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

□

4 The limit of $\text{SL}_n(q)$ is extremely amenable

5 Witts Lemma

6 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 24. *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 25. *Let $U \leq V$. Then $\dim U^\perp = \dim V - \dim U$.*

Lemma 26. *Let $U \leq V$. Then $U^{\perp\perp} = U$.*

Lemma 27. *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 25 $\dim e^\perp = n - 1$.

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 26 $U^\perp = \langle b_2, \dots, b_{n-1} \rangle$ 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 28. *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 29. 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 24 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 30. 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 31. 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 isomtry.

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 32 (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 33. 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 27 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 29 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 31 implies that the above map is also an isomtry. By Witt's lemma this isometry can be extended to an isometry $h: V \rightarrow V$.

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

Finally, we need to show that $hg \in H$, here the choice of H using Lemma 27 comes into play. By construction of h we have that $hg|_U = 1_U$. Therefore we can apply Lemma 28 and get that $hg(U^\perp) = U^\perp$. Hence $hg \in H$ and $d(g, hg) \leq \frac{8}{n}$. \square

7 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