Contents

Introduction

This is going to be a part of my Honors thesis independent study, focused on amenability and C*-algebras. This section of notes will be a deeper dive into group amenability. These notes will be taken from the notes my professor has prepared on group amenability, with supplementation from Volker Runde's *Lectures on Amenability* and Pierre de la Harpe's *Topics in Geometric Group Theory*.

I do not claim any of this work to be original.

Amenable Groups and Subgroups

Let G be a group, with $P(G)$ denoting the power set.

Definition. An invariant mean on G is a set function $m : P(G) \to [0,1]$, which satisfies, for all $t \in G$ and $E, F \subseteq G$,

(1) $m(G) = 1$;

(2) $m(E \sqcup F) = M(E) + m(F)$;

(3) $m(tE) = m(E)$.

We say G is amenable if it admits a mean.

We can also say that m is a translation-invariant probability measure on $(G, P(G))$.

Proposition (Amenability of Subgroups and Quotient Groups)**:** Let G be amenable, with $H \leqslant G$.

(1) H is amenable;

(2) for $H \trianglelefteq G$, G/H is amenable.

Proof.

(1) Let R be a right transversal for H (i.e., selecting one element of each right coset of H to make up R).

If m is a mean for G, we set

$$\lambda : \mathcal{P}(H) \to [0,1]$$

by $\lambda(E) = m(ER)$. We have

$$\begin{aligned}\lambda(H) &= m(HR)\\ &= m(G)\end{aligned}$$

$$= 1.$$

We claim that if $E \cap F = \emptyset$, then $ER \cap FR = \emptyset$, since if we suppose toward contradiction that $ER \cap FR \neq \emptyset$, then $xr_1 = yr_2$ for some $x \in E, y \in F$ and $r_1, r_2 \in R$. Then, we must have $r_2 r_1^{-1} = y^{-1}x \in H$, meaning $r_1 = r_2$ and $x = y$, which means $E \cap F \neq \emptyset$.

Thus, we have

$$\begin{aligned}\lambda(E \sqcup F) &= m((E \sqcup F)R) \\ &= m(ER \sqcup FR) \\ &= m(ER) + m(FR) \\ &= \lambda(E) + \lambda(F),\end{aligned}$$

and

$$\begin{aligned}\lambda(sE) &= m(sER) \\ &= m(ER) \\ &= \lambda(E).\end{aligned}$$

(2) For the canonical projection map $\pi : G \to G/H$ defined by $\pi(t) = tH$, we define

$$\lambda : P(G/H) \to [0,1]$$

by $\lambda(E) = m\left(\pi^{-1}(E)\right)$. We have

$$\begin{aligned}\lambda(G/H) &= m\left(\pi^{-1}(G/H)\right) \\ &= m(G) \\ &= 1,\end{aligned}$$

and

$$\begin{aligned}\lambda(E \sqcup F) &= m\left(\pi^{-1}(E \sqcup F)\right) \\ &= m\left(\pi^{-1}(E) \sqcup \pi^{-1}(F)\right) \\ &= m\left(\pi^{-1}(E)\right) + m\left(\pi^{-1}(F)\right) \\ &= \lambda(E) + \lambda(F).\end{aligned}$$

To show translation-invariance, we let $sH = \pi(s) \in G/H$, and $E \subseteq G/H$. Note that

$$\pi^{-1}(\pi(s)E) = s\pi^{-1}(E),$$

since for $r \in s\pi^{-1}(E)$, we have $r = st$ for $\pi(t) \in E$, so $\pi(r) = \pi(st) = \pi(s)\pi(t) \in \pi(s)E$.

Additionally, if $r \in \pi^{-1}(\pi(s)E)$, then $\pi(r) \in \pi(s)E$, so $\pi\left(s^{-1}r\right) \in E$, and $s^{-1}r \in \pi^{-1}(E)$. Thus, we have

$$\begin{aligned}\lambda(\pi(s)E) &= m\left(\pi^{-1}(\pi(s)E)\right) \\ &= m\left(s\pi^{-1}(E)\right) \\ &= m\left(\pi^{-1}(E)\right) \\ &= \lambda(E).\end{aligned}$$

$\square$

Understanding Free Groups

In the Tarski's Theorem notes, we discussed a little bit the ramifications of the free group on two generators being paradoxical. In order to better understand free groups, we will draw information from Pierre de la Harpe's *Topics in Geometric Group Theory* and Clara Löh's *Geometric Group Theory: An Introduction*.

Groups specified by Generating Sets

Definition. Let G be a group and $S \subseteq G$ be a subset. The subgroup generated by S is the intersection of all subgroups of G that contain S. We write $\langle S\rangle_G$. We say S generates G if $\langle S\rangle_G = G$.

A group is called finitely generated if it contains a finite subset that contains the group in question.

Definition (Characterization of a Generated Subgroup)**.** We can characterize a generated subgroup by S as follows:

$$\langle S\rangle_G = \left\{s_1^{\varepsilon_1}s_2^{\varepsilon_2}\cdots s_n^{\varepsilon_n} \;\middle|\; n \in \mathbb{N},\ s_1,\dots,s_n \in S,\ \varepsilon_1,\dots,\varepsilon_n \in \{-1,1\}\right\}.$$

Example (Generating Sets)**.**

- If G is a group, then G is a generating set of G.
- The trivial group is generated by the empty set.
- The set $\{1\}$ generates $\mathbb{Z}$, as does $\{2,3\}$. However, $\{2\}$ and $\{3\}$ alone do not generate $\mathbb{Z}$.
- Let X be a set. The symmetric group S_X is finitely generated if and only if X is finite.

Free Groups

Definition. Let S be a set. A group F containing S is said to be freely generated if, for every group G and every map $\varphi : S \to G$, there is a unique group homomorphism $\overline{\varphi} : F \to G$ extending φ. The following diagram commutes:

$$\begin{tikzcd} S \arrow[r, "\varphi"] \arrow[d, hook, "\iota"'] & G \\ F \arrow[ur, "\overline{\varphi}"'] & \end{tikzcd}$$

A group is free if it contains a free generating set.

Example.

- The additive group $\mathbb{Z}$ is freely generated by $\{1\}$. The additive group $\mathbb{Z}$ is *not* freely generated by $\{2,3\}$, or $\{2\}$, or $\{3\}$. In particular, not every generating set of a group contains a free generating set.
- The trivial group is freely generated by the empty set.
- Not every group is free — the additive groups $\mathbb{Z}/2\mathbb{Z}$ and $\mathbb{Z}\times\mathbb{Z}$ are not free.

We will use the universal property of free groups to show their uniqueness up to isomorphism.

Proposition: Let S be a set. Then, there is at most one group freely generated by S up to isomorphism.

Proof. Let F and F' be two groups freely generated by S, with inclusions of φ and φ' respectively. Because F is freely generated by S, there is a group homomorphism $\overline{\varphi}' : F \to F'$ that extends φ — i.e., that $\overline{\varphi}' \circ \varphi = \varphi'$.

Similarly, there is a group homomorphism $\overline{\varphi} : F' \to F$ with $\overline{\varphi} \circ \varphi' = \varphi$.

$$\begin{tikzcd} S \arrow[r, "\varphi'"] \arrow[d, hook, "\varphi"'] & F' \\ F \arrow[ur, "\overline{\varphi}'"'] & \end{tikzcd} \qquad \begin{tikzcd} S \arrow[r, "\varphi"] \arrow[d, hook, "\varphi'"'] & F \\ F' \arrow[ur, "\overline{\varphi}"'] & \end{tikzcd}$$

We will show that $\overline{\varphi} \circ \overline{\varphi}' = \mathrm{id}_F$, and $\overline{\varphi}' \circ \overline{\varphi} = \mathrm{id}_{F'}$. The composition $\overline{\varphi} \circ \overline{\varphi}'$ is a group homomorphism that makes the following diagram commute.

$$\begin{tikzcd} S \arrow[r, "\varphi"] \arrow[d, hook, "\varphi"'] & F \\ F \arrow[ur, "\overline{\varphi}\circ\overline{\varphi}'"'] & \end{tikzcd}$$

Since id_F is a group homomorphism contained in this diagram, and F is freely generated by S, we must have $\overline{\varphi} \circ \overline{\varphi}' = \mathrm{id}_F$. Similarly, we must have $\overline{\varphi}' \circ \overline{\varphi} = \mathrm{id}_{F'}$. □

Theorem (Existence of Free Groups)**:** Let S be a set. There exists a group freely generated by S. This group is unique up to isomorphism.

Proof. We want to construct a group consisting of "words" made up of the elements of S and their "inverses," then modding out by the natural cancellation rules.

We consider the alphabet

$$A = S \cup \hat{S}.$$

Here, $\hat{S} = \{\hat{s} \mid s \in S\}$ is a disjoint copy of S, such that $\hat{s}$ will serve as the inverse of s in the group we will construct.

We define A^* to be the set of all finite sequences over the alphabet A, including the empty word ϵ. We define the operation $A^* \times A^* \to A^*$ by concatenation. This operation is associative with neutral element ϵ.

We define

$$F(S) = A^*/\sim,$$

where $\sim$ is the equivalence relation generated by, for all $x, y \in A^*$ and $s \in S$, $xs\hat{s}y \sim xy$ and $x\hat{s}sy \sim xy$.

We denote the equivalence classes with respect to $\sim$ by $[\cdot]$.

Concatenation induces a well-defined operation $F(S) \times F(S) \to F(S)$ by

$$[x]\,[y] = [xy]$$

for $x, y \in A^*$.

We claim that $F(S)$ with the defined concatenation is a group. We can see that $[\epsilon]$ is a neutral element for the operation, and associativity of the operation is inherited from the associativity of the operation on A^*.

To find inverses, we define $I : A^* \to A^*$ by $I(\epsilon) = \epsilon$, and

$$\begin{aligned} I(sx) &= I(x)\hat{s} \\ I(\hat{s}x) &= I(x)s \end{aligned}$$

for all $x \in A^*$ and $s \in S$. Induction shows that $I(I(x)) = x$, and

$$[I(x)]\,[x] = [I(x)\,x]$$

$$= [\epsilon]$$

for all $x \in A^*$. Thus, we must also have

$$\begin{aligned}[x][I(x)] &= [I(I(x))][I(x)] \\ &= [\epsilon].\end{aligned}$$

Thus, we see that there are inverses in $F(S)$.

To see that $F(S)$ is freely generated by S, we let $\iota : S \to F(S)$ be the map given by sending a letter in $S \subseteq A^*$ to its equivalence class in $F(S)$. By construction, $F(S)$ is generated by the subset $\iota(S) \subseteq F(S)$.

We do not know yet that ι is injective, so we take a bit of a detour. We show that for every group G and every map $\varphi : S \to G$, there is a unique group homomorphism $\overline{\varphi} : F(S) \to G$ such that $\overline{\varphi} \circ \iota = \varphi$.

We construct a map $\varphi^* : A^* \to G$ inductively by

$$\begin{aligned}\epsilon &\mapsto e \\ sx &\mapsto \varphi(s)\varphi^*(x) \\ \hat{s}x &\mapsto (\varphi(s))^{-1}\varphi^*(x)\end{aligned}$$

for all $s \in S$ and $x \in A^*$. We can see that, since the definition of φ^* is compatible with the generating set of $\sim$, it is compatible with the equivalence relation of $\sim$ on A^*. Additionally, we can see that $\varphi^*(xy) = \varphi^*(x)\varphi^*(y)$ for all $x, y \in A^*$. Thus,

$$\begin{aligned}\overline{\varphi} : F(S) &\to G \\ [x] &\mapsto [\varphi^*(x)],\end{aligned}$$

is, as constructed, a group homomorphism, with $\overline{\varphi} \circ \iota = \varphi$. Since $\iota(S)$ generates $F(S)$, this group homomorphism is unique.

We must now show that ι is injective.

Let $s_1, s_2 \in S$. Consider the map $\varphi : S \to \mathbb{Z}$ given by $\varphi(s_1) = 1$ and $\varphi(s_2) = -1$. The corresponding homomorphism $\overline{\varphi} : F(S) \to G$ satisfies

$$\begin{aligned}\overline{\varphi}(\iota(s_1)) &= \varphi(s_1) \\ &= 1 \\ &\neq -1 \\ &= \varphi(s_2) \\ &= \overline{\varphi}(\iota(s_2)),\end{aligned}$$

meaning $\iota(s_1) \neq \iota(s_2)$. Thus, ι is injective. □

Free Groups, Free Products, and the Ping Pong Lemma

We can now consider free groups in a more categorical context — specifically, as a special type of free object. Whereas the previous section drew information from Clara Löh's *Geometric Group Theory: An Introduction*, this section will draw information from Pierre de la Harpe's *Topics in Geometric Group Theory*. Specifically, we are focused on chapter 2, which discusses free products, free groups, and the ping pong lemma (which will provide a more general proof of the paradoxicality of SO(3)).

Definition (Free Monoid)**.** A monoid is a set with multiplication that is associative and includes a neutral element.

Given a set A, the free monoid on A is the set $W(A)$ of finite sequences of elements of A (also known as words). We write an element of $W(A)$ as $w = a_1a_2\cdots a_n$, where each $a_j \in A$. We identify A with the subset of $W(A)$ of words with length 1.

Definition (Free Product)**.** Let $(\Gamma_i)_{i\in I}$ be a family of groups. Set

$$\begin{aligned} A &= \coprod_{i\in I} \Gamma_i \\ &= \{(g_i, i) \mid g_i \in \Gamma_i, i \in I\} \end{aligned}$$

to be the coproduct of this family.

Let $\sim$ be the equivalence relation generated by

$$\begin{aligned} we_iw' &\sim ww' && \text{where } e_i \in \Gamma_i \text{ is the neutral element} \\ wabw' &\sim wcw' && \text{where } a,b,c \in \Gamma_i,\ c = ab \text{ for some } i \in I \end{aligned}$$

for all $w, w' \in W(A)$. The quotient $W(A)/\sim$ with the operation of concatenation is a group, which is known as the free product of the groups $\{\Gamma_i\}_{i\in I}$. We write it as

$$\bigstar_{i\in I}\Gamma_i.$$

The inverse of the equivalence class for $w = a_1a_2\dots a_n$ is $w^{-1} = a_n^{-1}a_{n-1}^{-1}\cdots a_1^{-1}$. The neutral element is ϵ, which is the empty word.

A word $w = a_1a_2\cdots a_n \in W(A)$ with $a_j \in \Gamma_{i_j}$ is said to be reduced if $i_{j+1} \neq i_j$ and a_j is not the neutral element of Γ_{i_j}.

Proposition (Existence of the Free Product)**:** Let $\{\Gamma_i\}_{i\in I}$ be a family of groups, $A = \coprod_{i\in I}\Gamma_i$, and $\bigstar_{i\in I}\Gamma_i = W(A)/\sim$ be as above.

Then, any element in the free product $\bigstar_{i\in I}\Gamma_i$ is represented by a unique reduced word in $W(A)$.

Proof.

Existence: Consider an integer $n \geqslant 0$ and a reduced word $w = a_1a_2\cdots a_n$ in $W(A)$, an element $a \in A$, and the word $aw \in W(A)$. We set

$$\mathcal{R}(aw) = \begin{cases} w & a = e_i \\ aa_1a_2\cdots a_n & a \in \Gamma_i, a \neq e_i, i \neq k \\ ba_2\cdots a_n & a \in \Gamma_k, aa_1 = b \neq e_k \\ a_2\cdots a_n & a \in \Gamma_k, a_1 = a^{-1} \in \Gamma_k \end{cases},$$

where k is the index for which $a_1 \in \Gamma_k$.

Then, $\mathcal{R}(aw)$ is yet another reduced word, and $\mathcal{R}(aw) \sim aw$, meaning that any word $w \in W(A)$ is equivalent to some reduced word by inducting on the length of w.

Uniqueness: For each $a \in A$, Let $T(a) = \mathcal{R}(aw)$ be a self-map on the set of reduced words.

For each $w = b_1b_2\cdots b_n$, we set $T(w) = T(b_1)T(b_2)\cdots T(b_n)$. For $a, b, c \in \Gamma_i$ with $ab = c$, we have $T(a)T(b) = T(c)$, and $T(e_i) = \epsilon$ (the empty word) for all $i \in I$.

For each reduced word, notice that $T(w)\epsilon = w$.

Let w be some word in $W(A)$ with w_1, w_2 reduced words equivalent to w. Since $w_1 \sim w_2$, we have $T(w_1) = T(w_2)$, and

$$\begin{aligned} w_1 &= T(w_1)\,\epsilon \\ &= T(w_2)\,\epsilon \\ &= w_2. \end{aligned}$$

□

Corollary: Let $\{\Gamma_i\}_{i\in I}$ and $\Gamma = \bigstar_{i\in I}\Gamma_i$ as above. For each $i_0 \in I$, the canonical inclusion

$$\iota : \Gamma_{i_0} \to \Gamma$$

is injective.

Proof. For any $a \in \Gamma_{i_0} \setminus \{e_{i_0}\}$, $\iota(a)$ is represented by a unique one-letter reduced word not equivalent to the empty word. □

Now that we have an understanding of free products, we can conceptualize the free group as a particular type of free product.

Definition (Free Groups)**.** Let X be a set. The free group over X is the free product of a family of copies of $\mathbb{Z}$ indexed by X, denoted $F(X)$.

Equivalently, the free group over X is

$$F(X) = \bigstar_{a\in X} \langle a \rangle,$$

where $\langle a \rangle$ denotes the cyclic group generated by the element a.

We can also identify $F(X)$ with the set of reduced words in $X \sqcup X^{-1}$ (as was done in the previous subsection).

The cardinality of X is called the rank of $F(X)$.

If Γ is a group, then a free subset of Γ is a subset $X \subseteq \Gamma$ such that the inclusion $X \hookrightarrow F(X)$ extends to an isomorphism of $\langle X \rangle_\Gamma$ onto $F(X)$.

We can now state and prove a universal property for free products (which naturally simplifies in the case of a free group.)

Theorem (Universal Property for Free Products)**:** Let Γ be a group, and $\{\Gamma_i\}_{i\in I}$ be a family of groups. Let $\{h_i : \Gamma_i \to \Gamma\}_{i\in I}$ be a family of homomorphisms.

Then, there exists a unique homomorphism $h : \bigstar_{i\in I}\Gamma_i \to \Gamma$ such that the following diagram commutes for each $i_0 \in I$.

$$\begin{tikzcd} \Gamma_{i_0} \arrow[r, "h_{i_0}"] \arrow[d, hook, "\iota"'] & \Gamma \\ \bigstar_{i\in I}\Gamma_i \arrow[ur, "h"'] & \end{tikzcd}$$

In particular, if Γ is a group, X is a set, and $\phi : X \to \Gamma$ is a set map, there exists a unique homomorphism $\Phi : F(X) \to \Gamma$ such that $\Phi(x) = \phi(x)$ for each $x \in X$.

Proof. For a reduced word $w = a_1 a_2 \cdots a_n \in \bigstar_{i\in I}\Gamma_i$ with $a_j \in \Gamma_{i_j} \setminus \{e_{i_j}\}$, and $i_{j+1} \neq i_j$ for each $j \in \{1, \dots, n-1\}$, we set

$$h(w) = h_{i_1}(a_1)\, h_{i_2}(a_2) \cdots h_{i_n}(a_n),$$

which defines h uniquely in terms of h_i. □

Note that for any two sets X, Y, the universal property provides that any map $X \to Y$ extends canonically to a group homomorphism, $F(X) \to F(Y)$.

$$\begin{tikzcd} X \arrow[r] \arrow[d, hook] & Y \arrow[d, hook] \\ F(X) \arrow[r] & F(Y) \end{tikzcd}$$

We can now prove an important lemma that will be useful in understanding paradoxical groups.

Theorem (Ping Pong Lemma)**:** Let G be a group acting on a set X, and let Γ_1, Γ_2 be subgroups of G. Let $\Gamma = \langle \Gamma_1, \Gamma_2 \rangle$. Assume Γ_1 contains at least 3 elements and Γ_2 contains at least two elements.

Suppose there exist nonempty subsets $X_1, X_2 \subseteq X$ with $X_1 \triangle X_2 \neq \emptyset$, such that for all $\gamma_1 \in \Gamma_1$ with $\gamma_1 \neq e_G$, and for all $\gamma_2 \in \Gamma_2$ with $\gamma_2 \neq e_G$,

$$\begin{aligned} \gamma(X_2) &\subseteq X_1 \\ \gamma(X_1) &\subseteq X_2. \end{aligned}$$

Then, Γ is isomorphic to the free product $\Gamma_1 \star \Gamma_2$.

Proof. Let w be a nonempty reduced word spelled with letters from the disjoint union of $\Gamma_1 \setminus \{e_G\}$ and $\Gamma_2 \setminus \{e_G\}$. We must show that the element of Γ defined by w is not the identity.

If $w = a_1 b_1 a_2 b_2 \cdots a_k$ with $a_1, \dots, a_k \in \Gamma_1 \setminus \{e_G\}$ and $b_1, \dots, b_{k-1} \in \Gamma_2 \setminus \{e_G\}$. Then,

$$\begin{aligned} w(X_2) &= a_1 b_1 \cdots a_{k-1} b_{k-1} a_k (X_2) \\ &\subseteq a_1 b_1 \cdots a_{k-1} b_{k-1} (X_1) \\ &\subseteq a_1 b_1 \cdots a_{k-1} (X_2) \\ &\vdots \\ &\subseteq a_1 (X_2) \\ &\subseteq X_1. \end{aligned}$$

Since $X_2 \nsubseteq X_1$, this implies $w \neq e_G$.

If $w = b_1 a_2 b_2 a_2 \cdots b_k$, we select $a \in \Gamma_1 \setminus \{e_G\}$, and apply the previous argument to awa^{-1}. Since $awa^{-1} \neq e_G$, neither is w.

Similarly, if $w = a_1 b_1 \cdots a_k b_k$, we select $a \in \Gamma_1 \setminus \{e_G, a_1^{-1}\}$, and apply the argument to awa^{-1}, and if $w = b_1 a_2 b_2 \cdots a_k$, we select $a \in \Gamma_1 \setminus \{e_G, a_k\}$, and apply the argument to awa^{-1}. □

Example. We can use the Ping Pong Lemma to see that

$$\begin{aligned} A &= \begin{pmatrix} 1 & 2 \\ 0 & 1 \end{pmatrix} \\ B &= \begin{pmatrix} 1 & 0 \\ 2 & 1 \end{pmatrix} \end{aligned}$$

generate a subgroup of $SL(2, \mathbb{Z})$ which is free of rank 2.

Corollary: The special orthogonal group $SO(3)$ contains a subgroup isomorphic to the free group on two generators.

To prove this, we state a different version of the Ping Pong Lemma that we will apply to a particular space.

Theorem (Ping Pong Lemma for Cyclic Groups)**:** Let G act on a set X, and suppose there exist disjoint subsets $A_+, A_-, B_+, B_- \subseteq X$ whose union is not all of X. If there exist elements a and b in G such that

$$\begin{aligned} a \cdot (X \setminus A_-) &\subseteq A_+ \\ a^{-1} \cdot (X \setminus A_+) &\subseteq A_- \\ b \cdot (X \setminus B_-) &\subseteq B_+ \\ b \cdot (X \setminus B_+) &\subseteq B_-, \end{aligned}$$

then it is the case that the group generated by a and b is free of rank 2.

Proof of Corollary. We let

$$\begin{aligned} a &= \begin{pmatrix} 3/5 & 4/5 & 0 \\ -4/5 & 3/5 & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ a^{-1} &= \begin{pmatrix} 3/5 & -4/5 & 0 \\ 4/5 & 3/5 & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ b &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & 3/5 & -4/5 \\ 0 & 4/5 & 3/5 \end{pmatrix} \\ b^{-1} &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & 3/5 & 4/5 \\ 0 & -4/5 & 3/5 \end{pmatrix}. \end{aligned}$$

We specify

$$X = A_+ \sqcup A_- \sqcup B_+ \sqcup B_- \sqcup \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix},$$

where

$$\begin{aligned} A_+ &= \left\{ \frac{1}{5^k} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \middle| k \in \mathbb{Z}, x \equiv 3y \text{ modulo } 5, z \equiv 0 \text{ modulo } 5 \right\} \\ A_- &= \left\{ \frac{1}{5^k} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \middle| k \in \mathbb{Z}, x \equiv -3y \text{ modulo } 5, z \equiv 0 \text{ modulo } 5 \right\} \\ B_+ &= \left\{ \frac{1}{5^k} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \middle| k \in \mathbb{Z}, z \equiv 3y \text{ modulo } 5, x \equiv 0 \text{ modulo } 5 \right\} \\ B_- &= \left\{ \frac{1}{5^k} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \middle| k \in \mathbb{Z}, z \equiv -3y \text{ modulo } 5, x \equiv 0 \text{ modulo } 5 \right\}. \end{aligned}$$

To verify that the conditions of the Ping Pong Lemma hold, we calculate

$$\begin{pmatrix} 3/5 & 4/5 & 0 \\ -4/5 & 3/5 & 0 \\ 0 & 0 & 1 \end{pmatrix} \left(\frac{1}{5^k} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \right) = \frac{1}{5^{k+1}} \begin{pmatrix} 3x + 4y \\ -4x + 3y \\ 5z \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} 3/5 & -4/5 & 0 \\ 4/5 & 3/5 & 0 \\ 0 & 0 & 1 \end{pmatrix}\left(\frac{1}{5^k}\begin{pmatrix} x \\ y \\ z \end{pmatrix}\right) = \frac{1}{5^{k+1}}\begin{pmatrix} 3x-4y \\ 4x+3y \\ 5z \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 3/5 & -4/5 \\ 0 & 4/5 & 3/5 \end{pmatrix}\left(\frac{1}{5^k}\begin{pmatrix} x \\ y \\ z \end{pmatrix}\right) = \frac{1}{5^{k+1}}\begin{pmatrix} 5x \\ 3y-4z \\ 4y+3z \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 3/5 & 4/5 \\ 0 & -4/5 & 3/5 \end{pmatrix}\left(\frac{1}{5^k}\begin{pmatrix} x \\ y \\ z \end{pmatrix}\right) = \frac{1}{5^{k+1}}\begin{pmatrix} 5x \\ 3y+4z \\ -4y+3z \end{pmatrix}. \tag{4}$$

We verify that the conditions for the Ping Pong Lemma hold for each of these four conditions.

(1) For any vector

$$\frac{1}{5^k}\begin{pmatrix} x \\ y \\ z \end{pmatrix} \notin A_-,$$

we see that $k+1 \in \mathbb{Z}$, $x' = 3x + 4y \equiv 3(-4x+3y)$ modulo 5, and that $z' = 5z \equiv 0$ modulo 5.

(2) For any vector

$$\frac{1}{5^k}\begin{pmatrix} x \\ y \\ z \end{pmatrix} \notin A_+,$$

we see that $k+1 \in \mathbb{Z}$, $x' = 3x - 4y \equiv -3(4x+3y)$ modulo 5, and $z' = 5z \equiv 0$ modulo 5.

(3) For any vector

$$\frac{1}{5^k}\begin{pmatrix} x \\ y \\ z \end{pmatrix} \notin B_-,$$

we see that $k+1 \in \mathbb{Z}$, $z' = 4y + 3z \equiv 3(3y-4z)$ modulo 5, and $x' = 5x \equiv 0$ modulo 5.

(4) For any vector

$$\frac{1}{5^k}\begin{pmatrix} x \\ y \\ z \end{pmatrix} \notin B_+,$$

we see that $k+1 \in \mathbb{Z}$, $z' = -4y + 3z \equiv -3(3y+4z)$ modulo 5, and $x' = 5x \equiv 0$ modulo 5.

Since we have verified that the conditions for the Ping Pong Lemma hold for each of the conditions, we have that $\{a, b\} \subseteq SO(3)$ generate a group isomorphic to the free group on two generators. □

The Normed Space $\ell_\infty(G)$

Definition. Let G be a group.

(1) The space $\mathcal{F}(G, \mathbb{R})$ is defined by

$$\mathcal{F}(G, \mathbb{R}) = \{f \mid f : G \to \mathbb{R} \text{ is a function}\}.$$

(2) A function $f \in \mathcal{F}(G, \mathbb{R})$ is positive if $f(x) \geqslant 0$ for all $x \in G$.

(3) A function $f \in \mathcal{F}(G, \mathbb{R})$ is simple if $\operatorname{Ran}(f)$ is finite. We say

$$\Sigma = \left\{ f : \mathcal{F}(G, \mathbb{R}) \,\middle|\, f \text{ is simple} \right\}.$$

Fact. $\Sigma \subseteq \mathcal{F}(G, \mathbb{R})$ is a subspace. To see this, if f, g are such that $\operatorname{Ran}(f), \operatorname{Ran}(g)$ are finite, and $\alpha \in \mathbb{R}$, then

$$\operatorname{Ran}(f + \alpha g) \leqslant \operatorname{Ran}(f) + \operatorname{Ran}(g),$$

so $f + \alpha g$ has finite range.

Definition. For $E \subseteq G$, set

$$\mathbb{1}_E : G \to \mathbb{R}$$

defined by

$$\mathbb{1}_E(x) = \begin{cases} 1 & x \in E \\ 0 & x \notin E \end{cases}.$$

This is the characteristic function of E.

Fact.

$$\operatorname{span}\{\mathbb{1}_E \mid E \subseteq G\} = \Sigma.$$

Proof. We see that $\mathbb{1}_E \in \Sigma$ for any $E \subseteq G$, and Σ is a subspace.

If $\phi \in \Sigma$, with $\operatorname{Ran}(\phi) = \{t_1, \dots, t_n\}$ with t_i distinct, we set

$$E_i = \phi^{-1}(\{t_i\}),$$

meaning

$$\phi = \sum_{i=1}^{n} t_i \mathbb{1}_{E_i}.$$

□

Definition.

(1) A function $f \in \mathcal{F}(G, \mathbb{R})$ is bounded if there exists $M > 0$ such that $\operatorname{Ran}(f) \subseteq [-M, M]$.

(2) The space $\ell_\infty(G)$ is defined by

$$\ell_\infty(G) = \{f \in \mathcal{F}(G, \mathbb{R}) \mid f \text{ is bounded}\}.$$

(3) The norm on $\ell_\infty(G)$ is defined by

$$\|f\| = \sup_{x \in G} |f(x)|.$$

Proposition: The space $\ell_\infty(G)$ is complete, Additionally, $\overline{\Sigma} = \ell_\infty(G)$.

Proof. Let $(f_n)_n$ be Cauchy. For $x \in G$, it is the case that

$$\begin{aligned} |f_n(x) - f_m(x)| &= |(f_n - f_m)(x)| \\ &\leqslant \|f_n - f_m\|, \end{aligned}$$

meaning $(f_n(x))_n$ is Cauchy in $\mathbb{R}$. We define $f(x) = \lim_{n\to\infty} f_n(x)$. We must show that $f \in \ell_\infty(G)$ and $\|f_n - f\| \to 0$.

$$\begin{aligned}|f(x)| &= \left|\lim_{n\to\infty} f_n(x)\right| \\ &= \lim_{n\to\infty} |f_n(x)| \\ &\leqslant \limsup_{n\to\infty} \|f_n\| \\ &\leqslant C,\end{aligned}$$

as Cauchy sequences are always bounded. Thus, $\sup_{x\in G} |f(x)| \leqslant C$.

Given $\varepsilon > 0$, we find N such that for all $m, n \geqslant N$, $\|f_n - f_m\| \leqslant \varepsilon$. Thus, for $x \in G$, we have

$$\begin{aligned}|f_n(x) - f)m(x)| &\leqslant \|f_n - f_m\| \\ &\leqslant \varepsilon.\end{aligned}$$

Taking $m \to \infty$, we get $|f_n(x) - f(x)| \leqslant \varepsilon$ for all $n \geqslant N$, meaning $\|f_n - f\| \leqslant \varepsilon$ for all $n \geqslant N$.

Now, for $f \in \ell_\infty(G)$, let $\operatorname{Ran}(f) \subseteq [-M, M]$ for some $M > 0$. Let $\varepsilon > 0$. Since $[-M, M]$ is compact, it is totally bounded, so we can find intervals $I_1, \dots, I_n$ with $[-M, M] = \bigsqcup_{k=1}^{n} I_k$, with the length of each I_k less than ε.

Set $E_k = f^{-1}(I_k)$. Pick $t_k \in I_k$. Then, we set

$$\phi = \sum_{i=1}^{n} t_k \mathbb{1}_{E_k}.$$

We see that $\|\phi - f\| < \varepsilon$. ◻

Corollary: For any $f \in \ell_\infty(G)$, there is a sequence $(\phi_n)_n$ in Σ with $\|\phi_n - f\| \to 0$. If $f \geqslant 0$, then it is possible to select $\phi_n \geqslant 0$.

Proposition: Let G be a group. There is an action

$$G \xrightarrow{\lambda_s} \operatorname{Isom}(\ell_\infty(G))$$

defined by

$$\lambda_s(f)(t) = f\left(s^{-1}t\right).$$

Proof. We have

$$\begin{aligned}\lambda_s(f + \alpha g)(t) &= (f + \alpha g)\left(s^{-1}t\right) \\ &= f\left(s^{-1}t\right) + \alpha g\left(s^{-1}t\right) \\ &= \lambda_s(f)(t) + \alpha\lambda_s(g)(t) \\ &= (\lambda_s(f) + \alpha\lambda_s(g))(t).\end{aligned}$$

Thus, λ_s is a linear operator.

We have

$$\|\lambda_s(f)\| = \sup_{t\in G} |\lambda_s(f)(t)|$$

$$= \sup_{t \in G} \left| f\left(s^{-1}t\right) \right|$$
$$= \|f\|,$$

hence

$$\begin{aligned} \|\lambda_s(f) - \lambda_s(f)\| &= \|\lambda_s(f-g)\| \\ &= \|f-g\|. \end{aligned}$$

Thus, λ_s is an isometry.

We have

$$\begin{aligned} \lambda_s \circ \lambda_r(f)(t) &= \lambda_r(f)\left(s^{-1}t\right) \\ &= f\left(r^{-1}s^{-1}t\right) \\ &= f\left((sr)^{-1}t\right) \\ &= \lambda_{sr}(f)(t), \end{aligned}$$

meaning $\lambda_s \circ \lambda_r = \lambda_{sr}$. □

Remark: By a similar process, we find that $\lambda_s(\mathbb{1}_E) = \mathbb{1}_{sE}$ for any subset $E \subseteq G$ and $s \in G$.

Definition. A state on $\ell_\infty(G)$ is a continuous linear functional $\mu \in (\ell_\infty(G))^*$ that satisfies the following.

(1) μ is positive;

(2) $\mu(\mathbb{1}_G) = 1$.

A state is called left-invariant if

$$\mu(\lambda_s(f)) = \mu(f).$$