

FURTHER GROUP THEORY

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Last updated: October 16, 2019

<https://www.overleaf.com/project/5d99f689a31d2a00016a0303>

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0 Introduction

These are my notes for Further Group Theory, taught by Dr. Vaibhav Gadre. The topics and their ordering generally follow the book *Groups, Graphs, and Trees* by John Meier.

0.1 Notation

1 Cayley's Theorems

In this course we often consider symetries of some object. If X is a mathematical object then we use $\text{SYM}(X)$ to denote all bijections form X to X that preserve some structure. For example if X is the set $[n] = \{1, 2, \dots, n\}$ then $\text{SYM}(X)$ is the symmetric group of order n , denoted SYM_n .

1.1 Cayley's "Basic" Theorem

Definition 1.1.1

An action of a group G on a set X is a group homomorphism from G to $\text{SYM}(X)$. Equivalently, its a map from $G \times X \rightarrow X$ such that

1. $e \cdot x = x$, for all $x \in X$; and
2. $(gh) \cdot x = g \cdot (h \cdot x)$ for all $g, h \in G$ and $x \in X$.

We denote " G acts on X " by $G \curvearrowright X$. The associated homomorphism is a *representation* of G . If the representation is injective then it is *faithful*.

For this course all group actions are on the left, this will be important later when defining Cayley graphs.

Theorem 1.1.2: Cayley's Theorem

Every group can be faithfully represented as a group of permutations

Proof. We can view a group G as acting "on its own elements", meaning that each element of G can be viewed as a permutation of the elements of G . Specifically, the permutation associated to $g \in G$ is $\pi_g(h) = gh$ for all $h \in G$. This clearly must be a permutation since $gh = gh'$ would imply that $h = h'$. Thus we have a map $g \mapsto \pi_g \in \text{SYM}(G)$.

It is easy to see that this mapping is a group homomorphism, so all that is left to check is that this representation is faithful. To do this, note that the kernel of this homomorphism is only the identity element. \square

1.2 Graphs

Definition 1.2.1

A graph Γ consists of a set of vertices $V(\Gamma)$ and a set of edges $E(\Gamma)$, where each edge e is associated to a pair of vertices, $\text{ENDS}(e) = \{u, v\} \in V$

Note that there can be multiple edges between two vertices and an edge e can be a loop that where $\text{ENDS}(e) = \{v\}$. A graph with out multiple edges or loops is a *simple graph*. The *valence* of a vertex is the number of edges that contain it, and a graph is *locally finite* if the valence of every vertex is finite.

A *path* is a set of alternating vertices and edges $\{v_0, e_1, v_1, \dots, v_{n-1}, e_n, v_n\}$ where $\text{Ends}(e_i) = \{v_{i-1}, v_i\}$. A graph is *connected* if any two vertices can be joined by a path. A *backtrack* is a path of the form $\{v, e, w, e, v\}$. A path is *reduced* if it contains no backtracks. A cycle is a path that begins and ends at the same point. A *tree* is a connected graph that has no cycles.

Proposition 1.2.2

The following conditions on a connected graph Γ are equivalent:

1. Γ is a tree.
2. Given any two vertices v, w there is a unique reduced edge path from v to w .
3. For every edge e removing e disconnects the graph.
4. If Γ is finite, then $|V(\Gamma)| = |E(\Gamma)| + 1$.

■ *Proof.* Left as an exercise. □

Definition 1.2.3

A *regular m -tree* is a tree where every vertex has valance m . For a given m this tree is unique and denoted \mathcal{T}_m . A graph is a *biregular tree* if it is bipartite and all of the vertices in one class have valance m and all vertices in the other class have valance n . Given m and n there is a unique biregular tree $\mathcal{T}_{m,n}$.

Definition 1.2.4

A *directed* graph is a graph where each edge is an ordered pair of vertices, meaning that edges have a beginning and an end.

A directed graph is connected when its underlying undirected graph is, we do not consider directed connectedness.

There can also be decorations on the graph, such as a function $V(\Gamma) \rightarrow \mathcal{L}$ where \mathcal{L} is some set of labels.

1.3 Symmetry Groups of Graphs

Definition 1.3.1

A *symmetry* of a graph Γ is a bijection α that takes vertices to vertices and edges to edges such that if for some edge e , $\text{ENDS}(e) = \{v, w\}$, then $\text{ENDS}(\alpha(e)) = \{\alpha(v), \alpha(w)\}$. The *symmetry group* of Γ is the collection of all its symmetries, where the group operation is composition, denoted $\text{SYM}(\Gamma)$.

Example 1.3.2

The symmetry group of the complete graph K_n is isomorphic to SYM_n

Definition 1.3.3

Let G be a subgroup of $\text{SYM}(\Gamma)$. We say that G is *vertex transitive* if for any two vertices v, v' there is some $g \in G$ such that $g(v) = v'$. Similarly, G is *edge transitive* if for any two edges e, e' there is some $g \in G$ such that $g(e) = e'$. A *flag* is a pair (v, e) where $v \in \text{ENDS}(e)$. G is *flag transitive* if for any two flags $(v, e), (v', e')$ there is some $g \in G$ such that $g(v) = v'$ and $g(e) = e'$.

We can further say that G is *simply transitive* on the vertices (or edges or flags) if it is vertex (or edge or flag) transitive and for any two v, v' there is a unique $g \in G$ such that $g(v) = v'$ (respectively $e, e', g(e) = e'$, etc).

Example 1.3.4

The symmetry group of the complete bipartite graph $K_{m,n}$ is not vertex transitive if for $m \neq n$. This is because symmetries preserve valance so vertices of one class can never be taken to vertices of another class under a symmetry.

Lemma 1.3.5

If Γ is a directed graph then the collection of all symmetries that preserve every edges direction form a subgroup of $\text{SYM}(\Gamma)$.

Proof. Clearly this collection is a subset of $\text{SYM}(\Gamma)$, so we must show that it is closed under composition and contains all inverses. If g and h preserve edge directions then so do their inverses and gh . \square

An almost identical proof shows the following.

Lemma 1.3.6

If the edges and/or the vertices of a graph Γ are labeled then the collection of all symmetries that preserve the labeling form a subgroup of $\text{SYM}(\Gamma)$.

Definition 1.3.7

If a graph Γ comes with certain decorations, then let $\text{SYM}^+(\Gamma)$ be the subgroup of $\text{SYM}(\Gamma)$ that preserve all decorations.

1.4 Orbits and Stabilizers

Definition 1.4.1

Let a group G act on X . If $x \in X$ then the *stabilizer* of x is

$$\text{Stab}(x) = \{g \in G \mid g \cdot x = x\}.$$

For a given element $x \in X$, the identity element of G fixes x , and for any $g, h \in G$ that fix x , so do their inverses and gh . Thus, for any $x \in X$ $\text{Stab}(x)$ is a subgroup of G .

Example 1.4.2

D_n is the group of symmetries of a regular n -gon. If x is a vertex of this n -gon, then there are two elements that fix x : the identity, and the reflection over the axis that contains x . Thus $\text{Stab}(x) \approx \mathbb{Z}_2$.

On the other hand, if x is the center of the n -gon then $\text{Stab}(x) \approx D_n$.

Example 1.4.3

If $\text{SYM}_n \curvearrowright [n]$ then $\text{Stab}(i) \approx \text{SYM}_{n-1}$. This is because we can take all permutations of the $n - 1$ elements that are not i and this forms $\text{Stab}(i)$.

Definition 1.4.4

Let $G \curvearrowright X$. The *orbit* of some element $x \in X$ is

$$\text{Orb}(x) = \{x \in X \mid x = g \cdot x \text{ for some } g \in G\}$$

For some $G \curvearrowright X$, pick a fixed x . Then $g \cdot x = h \cdot x$ if and only if $gh^{-1} \cdot x = x$, which is equivalent to $gh^{-1} \in \text{Stab}(x)$. Thus $g \cdot x = h \cdot x$ if and only if the left cosets $g\text{Stab}(x) = h\text{Stab}(x)$. This means that the mapping $g \cdot x \leftrightarrow g\text{Stab}(x)$ is a well defined bijective correspondence between the orbit of x and the left cosets of its stabilizer. This gives us the following.

Theorem 1.4.5: Orbit-Stabilizer Theorem

Let G be any finite group acting on X . Then for any $x \in X$,

$$|G| = |\text{Stab}(x)| \cdot |\text{Orb}(x)|.$$

Proof. The order of G is the order of $\text{Stab}(x)$ times the index of $\text{Stab}(x)$ in G . We have shown that the index of $\text{Stab}(x)$ in G (the number of left cosets) is the order of the orbit of x . \square

This theorem, among other things, shows that if the stabilizer of an element is trivial, then the elements of its orbit correspond to group elements.

1.5 Generating Sets

Definition 1.5.1

If G is a group and S is a subset of its elements, then S *generates* G if every element of G can be expressed as a product of elements of S and inverses of elements of S . A group is *finitely generated* if it has a finite generating set.

The generating set for a group is not unique. In fact even the smallest generating set is not unique as seen the the example below.

Example 1.5.2

in D_n any reflection along with the “minimal” rotation by $2\pi/n$ is a generating set. Any two adjacent reflections are also a generating set.

We can also note that every finite group must be finitely generated because the set of all elements forms a generating set.

Example 1.5.3

The rational numbers are not finitely generated. We assume that the operation is addition.

Suppose for contradiction that they are, and $S = \{n_1/d_1, n_2/d_2, \dots, n_k/d_k\}$ is a finite generating set. Then every element generated by this set can be expressed as some n/d where $d = \text{LCM}(d_1, d_2, \dots, d_k)$. But obviously not every element of \mathbb{Q} can be expressed in this way.

1.6 Cayley Graphs

Theorem 1.6.1: Cayley’s Better Theorem

Every finitely generated group can be faithfully represented as a symmetry group of a connected, directed, locally finite graph.

Proof. For a given group G , we need a graph such that G can be faithfully represented as a symmetry group of that graph. Instead of looking for one, we will construct one, $\Gamma G, S$. The vertices of $\Gamma_{G,S}$ correspond to the elements of G , and are denoted as v_g for $g \in G$. There is an edge from g to g' if there is some $s \in S$ such that $gs = g'$. Thus every edge corresponds to right multiplication of its initial vertex by a generator.

To show that $GG_{G,S}$ is connected, note that since S generates G , there is a path from every vertex to the vertex corresponding to the identity element. Thus there is a path from any given vertex to any other vertex. The valance of every vertex will clearly be finite since S is finite, so $\Gamma_{G,S}$ is locally finite.

The proof of Cayley’s basic theorem described the group action of G on the vertices $\Gamma_{G,S}$: $g \cdot v_h \mapsto v_{gh}$. In order for this to be a symmetry of $GG_{G,S}$, this action must extend to an action on the edges. We see that if there is an edge e from v_{h_1} to v_{h_2} then there is some $s \in S$ such that $h_1s = h_2$. If we take the action of g on these vertices we see that $g \cdot v_{h_1} = v_{gh_1}$ and $g \cdot v_{h_2} = v_{gh_2} = v_{gh_1s}$, meaning there is an edge between the images of the two vertices. Thus we can define an action of G on the edges as well. \square

Definition 1.6.2

Given a group G and a finite generating set S , we call $\Gamma_{G,S}$ the Cayley graph of G with respect to S .

There is an obvious way to label the edges of $\Gamma_{G,S}$: if an edge is from v_g to v_{gs} label it as s . The action of G on $\Gamma_{G,S}$ preserves the orientation and labeling so we conclude that $G < \text{SYM}^+(\Gamma_{G,S})$

1.6.1 Cayley Graphs of Dihedral Groups

Dihedral groups can be generated by a set of two adjacent reflections or by a set consisting of a minimal rotation and a reflection. These different generating sets give very different looking Cayley graphs.

One trick to generate the Cayley graph with respect to either of these two generating sets is as follows. Choose a point in “general position” the regular n -gon, meaning that its stabilizer is trivial. This will imply that the elements of the orbit of this point will correspond to elements of D_n . By applying the actions of the elements generating set repeatedly to the point and drawing the corresponding edges, you will draw the Cayley graph.

This trick can be used to find the Cayley graphs for other groups that represent some symmetries of a geometric object. For example S_4 can represent the symmetries of a tetrahedron and picking a point on the boundary of the tetrahedron that has a trivial stabilizer can reveal the Cayley graph of S_4 .

1.7 Symmetries of Cayley Graphs

Theorem 1.7.1

Let $\Gamma_{G,S}$ be the Cayley Graph of G with respect to the finite generating set S . Consider $\Gamma_{G,S}$ to be decorated with directions on its edges and labeling of its edges, corresponding to the generating set S . Then $\text{SYM}^+(\Gamma_{G,S}) \approx G$.

Proof. The left action of G on $\Gamma_{G,S}$ defined in the proof of Cayley’s “better” theorem shows that there is an injective homomorphism $G \rightarrow \text{SYM}(\Gamma_{G,S})$. Since the edges are defined through right multiplication and this group action is a left action, the edge labeling is preserved by the group action. Thus we have that we have an injective homomorphism $G \rightarrow \text{SYM}^+(\Gamma_{G,S})$.

To show that this homomorphism is surjective, consider an $\gamma \in \text{SYM}^+(\Gamma_{G,S})$. For any element $g \in G$ let v_g be the corresponding vertex in $\Gamma_{G,S}$. Then there is some g such that $\gamma(v_e) = v_g$. Then if we consider g as a symmetry of $\Gamma_{G,S}$, $g^{-1}\gamma \in \text{SYM}^+(\Gamma_{G,S})$. This symmetry fixes v_e and fixes all of the edges leaving or going to v_e since symmetries in $\text{SYM}^+(\Gamma_{G,S})$ preserve the labeling and orientation of edges. This means that $g^{-1}\gamma$ fixes all of the vertices adjacent to v_e , and following a similar argument, it fixes all of the vertices adjacent to those vertices. Thus we get that $g^{-1}\gamma$ is the identity which means that $g = \gamma$. Thus we conclude that the homomorphism that we had from G to $\text{SYM}^+(\Gamma_{G,S})$ is an isomorphism. \square

1.8 Fundamental Domains and Generating Sets

In what follows we think of graphs as geometric objects consisting of unit intervals joined together at vertices. Thus we can consider closed subsets of a graph.

Lemma 1.8.1

If a group G acts on a connected graph Γ then there is a subset $\mathcal{F} \subset \Gamma$ such that

1. \mathcal{F} is closed,
2. the set $\{g \cdot \mathcal{F} \mid g \in G\}$ covers Γ , and
3. no proper subset of \mathcal{F} satisfies properties (1) and (2).

■ *Proof.* FINISH ME LATER

□

ALSO INSERT SOME EXAMPLES

Theorem 1.8.2

Let G act on a connected graph Γ with fundamental domain \mathcal{F} . Then the set of elements

$$S = \{g \in G \mid g \neq e \text{ and } g \cdot \mathcal{F} \cap \mathcal{F} \neq \emptyset\}$$

is a generating set for G .

Proof. Pick and $g \in G$ the goal is to show that can be expressed as a combination of elements from S . Pick any $v \in \mathcal{F}$ and pick some path p connecting v to $g \cdot v$. Then let $\{\mathcal{F}, g_1\mathcal{F}, \dots, g_n\mathcal{F} = g\mathcal{F}\}$ be a finite sequence of images of \mathcal{F} such that

1. the entire path p is contained in $\cup g_i\mathcal{F}$ and
2. $g_i\mathcal{F} \cap g_{i+1}\mathcal{F} \neq \emptyset$ where g_0 is the identity.

We must show that such a sequence exists. The first condition can be met because $G \cdot \mathcal{F}$ covers all of Γ . The second condition can be met as a result of \mathcal{F} being closed.

Since $\mathcal{F} \cap g_1\mathcal{F} \neq \emptyset$, we know that $g_1 \in S$ by definition. Since $g_1\mathcal{F} \cap g_2\mathcal{F} \neq \emptyset$, $\mathcal{F} \cap g_1^{-1}g_2\mathcal{F} \neq \emptyset$, so $g_1^{-1}g_2 \in S$. Thus $g_2 = g_1(g_1^{-1}g_2)$ is a product of elements from S . Continuing in this way shows that g can be written as a product of elements from S . □

Theorem 1.8.3

Let $G \curvearrowright \Gamma$ with the fundamental domain \mathcal{F} . Further assume that if $g \cdot \mathcal{F} = \mathcal{F}$ then $g = e$. If $H < G$ and a fundamental domain for the induced action $H \curvearrowright \Gamma$ is a union of n copies of \mathcal{F} , ($n \in \mathbb{N} \cup \infty$), then the index of H in G is n .

Proof. Since we assumed that the only element that fixes \mathcal{F} is the identity, there is some point $x \in \mathcal{F}$ that is moved freely by G . This means that there is a bijection between the elements of $\text{Orb}(x)$ and the elements of G . We can explicitly write out the fundamental domain for $H \curvearrowright \Gamma$ as

$$\mathcal{F}_H = \cup_{i=1}^n g_i\mathcal{F},$$

where $n \in \mathbb{N} \cup \infty$, and the g_i are distinct elements of G . Then since \mathcal{F}_H is a fundamental domain, for all $g \cdot x$ there is some $h \in H$ such that $g \cdot x \in h\mathcal{F}_H$. This means that $g \cdot x \in (hg_i)\mathcal{F}$ for some g_i . Since any gx is contained in some $hg_i\mathcal{F}$ and the elements of the orbit of x correspond to the elements of G , we get that $G = \cup Hg_i$. This means that the set of g_i contains all of the coset representatives of H in G , and now we will show that no two g_i represent the same coset.

Suppose for contradiction that $Hg_i = Hg_j$ for some distinct g_i, g_j . Then $g_i g_j^{-1} \in H$. Now consider $\mathcal{F}'_H = \mathcal{F}_H \setminus g_j\mathcal{F}$. We claim that this still covers Γ through the actions of H . The situation that we must check is when some element of Γ $y \in hg_j\mathcal{F}$, for $h \in H$. In this case for some $h' \in H$, $y \in h'(g_i g_j^{-1} g_j\mathcal{F} = h'g_i\mathcal{F} \subset h'\mathcal{F}'_H$, proving that y is covered by \mathcal{F}'_H . But this contradicts \mathcal{F}_H being a fundamental domain so we conclude that for any distinct g_i, g_j , $Hg_i \neq Hg_j$, meaning that the set of g_i correspond to the right cosets of H in G , meaning that the order of H in G is n . □

1.9 Words and Paths

Given a set S , a finite sequence of elements of S (possibly with repetition) is called a *word*. The set S is called the *alphabet*. The collection of all words, including the empty word, is denoted S^* .

S^{-1} denotes the set of all formal inverses of elements in S . Then we can also make the set of words $(S \cup S^{-1})^*$. We can take formal inverses of words of this form in the usual way $(x_1 x_2 \dots x_n)^{-1} = x_n^{-1} \dots x_2^{-1} x_1^{-1}$.

Given any word $\omega \in (S \cup S^{-1})^*$, there is an associated path in the directed and edge labeled Cayley graph $\Gamma_{G,S}$. Similarly, there is a word for every finite edge path in $\Gamma_{G,S}$.

This means that we can think of the Cayley graph $\Gamma_{G,S}$ as a “calculator” for G . More formally, if we have group elements g, h and words ω_g, ω_h that correspond to g, h , then we can find gh by starting at the vertex v_e , following the path corresponding to ω_g , and then from that point follow the path corresponding to ω_h . This will result in the vertex v_{gh} that corresponds to gh .

2 Groups Acting on Trees

2.1 Free Groups

Definition 2.1.1

Let $S = \{x_1, \dots, x_n\}$ be a set of elements in a group G . A word $\omega \in \{S \cup S^*\}$ is said to be *freely reduced* if it does not contain a subword consisting of an element adjacent to its formal inverse. The group G is the *free group with basis S* if S is a set of generators for G and no freely reduced word or its inverse represents the identity element. The *rank* of a free group with basis S is the number of elements in S . \mathbb{F}_n is the free group of rank n .

There are also free groups of infinite order, but we will not consider them for now.

Theorem 2.1.2

For any $n \in \mathbb{N}$ there is a free group of rank n .

Proof. (Sketch)

Let $S = \{x_1, \dots, x_n\}$ be a set of n distinct symbols. Then we define the equivalence relation on all words in $\{S \cup S^*\}$ induced by

$$a_1 \cdots a_{i-1} a_i a_i^{-1} a_{i+1} \cdots a_k \sim a_1 \cdots a_{i-1} a_{i+1} \cdots a_k$$

where adjacent pairs of elements that are each others inverses get cancelled. Then the elements of the group \mathbb{F}_n are the equivalence classes of words. It is easy to check that this defines a group structure. The reason that we could not just let \mathbb{F}_n be the set of freely reduced words is that the product of two freely reduced words may not be freely reduced. \square

Proposition 2.1.3

The Cayley graph of \mathbb{F}_2 with respect to $\{x, y\}$ is an oriented version of T_4 .

Proof. Since \mathbb{F}_2 is generated by two elements, every vertex in the Cayley graph will have valance 4. Recall that there is a correspondence between freely reduced words and paths in a Cayley graph. Since no non empty freely reduced word is the identity element, we can deduce that no path is a cycle in the Cayley graph. Thus we know that the Cayley graph is a tree and that every vertex has valance 4, so it must be an oriented version of T_4 . \square

We know that \mathbb{F}_2 acts on T_4 . Specifically, we can view the action of x as a “shift to the right” of the graph, while the action of y is “a vertical shift upwards”.

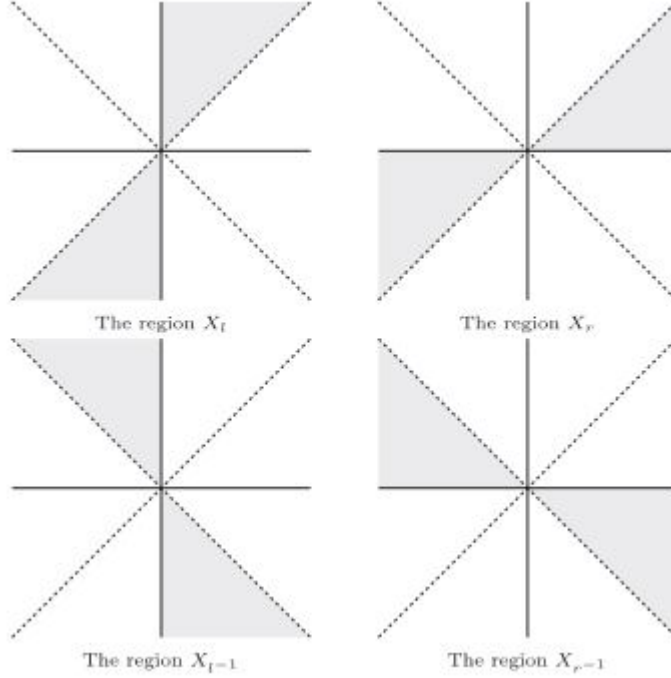
Note again that visualizing the action of an element of a group on a Cayley graph is not the same as following the path from the identity to that element in the Cayley graph. The action is a right action, while paths are determined through left multiplication.

2.1.1 Free Groups as Subgroups

Proposition 2.1.4

Consider $SL_2(\mathbb{Z})$, the group of two-by-two matrices with integer entries and determinant 1. The subgroup of $SL_2(\mathbb{Z})$ generated by $S = \left\{ \begin{bmatrix} 1 & 0 \\ 2 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 2 \\ 0 & 1 \end{bmatrix} \right\}$ is isomorphic to \mathbb{F}_2 .

Proof. We could try to show that no reduced word made with elements of S and S^{-1} is equal to the identity matrix directly, but this would be quite difficult. Instead we will do this using the action of $SL_2(\mathbb{Z})$ on the plane. Let $l = \begin{bmatrix} 1 & 0 \\ 2 & 1 \end{bmatrix}$, and $r = \begin{bmatrix} 1 & 2 \\ 0 & 1 \end{bmatrix}$. We want to show that any freely reduced word in $\{l, l^{-1}, r, r^{-1}\}$ does not represent the identity element. We partition the plane into regions, each of which are associated to a generator, as shown below.



Through computations, one can show that if $w \in \{l, l^{-1}, r, r^{-1}\}$, then $w \cdot X_y \subset X_w$ if $y \neq w^{-1}$. This containment is always proper. Now let ω be a freely reduced word. To show that ω is not the identity, it suffices to show that ω acts non-trivially on the plane. Since ω is freely reduced, we can apply the containment property one element at a time:

$$\begin{aligned} \omega \cdot X_{w_n} &= w_1 w_2 \cdots w_n \cdot X_{w_n} \subset w_1 w_2 \cdots w_{n-1} \cdot X_{w_n} \\ &\subset w_1 w_2 \cdots w_{n-2} \cdot X_{w_{n-1}} \subset \cdots \subset X_{w_1} \end{aligned}$$

This means that $\omega \cdot X_{w_n}$ is a proper subset of X_{w_1} , which makes it impossible that $\omega \cdot X_{w_n} = X_{w_n}$. This means that ω is not the identity element. \square

We will find another free group inside of a larger group. This time, consider the group $\text{Homeo}(\mathbb{R})$, the group of homeomorphisms from \mathbb{R} to \mathbb{R} . Specifically, we will use two functions to generate a free subgroup.

For the first function consider $\hat{f} = \begin{cases} 4x & \text{if } 0 \leq x \leq 1/5 \\ (4/5) + (1/4)(x - 1/5) & \text{if } 1/5 \leq x \leq 1 \end{cases}$. FINISH ME

Proposition 2.1.5
FINISH ME

2.2 Free group Homomorphisms and Group Presentations