

Lecture Notes by Jonathan Alcaraz (UCR)

Algebra

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Based on Lectures by

Dr. David Rush
University of California, Riverside

Lecture 1 23 Sep 2016

Definition 1.1 A *monoid* is a set together with a binary operation that is associative and has an identity (usually denoted e).

Example The collection of maps from a set to itself is a monoid with respect to composition.

Definition 1.2 An element x of a monoid G is said to be *invertible* if there exists some $y \in G$ such that $xy = yx = e$. It follows that such an element is unique. We call such an element the *inverse* of x and usually denote it by x^{-1} .

Definition 1.3 A monoid in which every element is invertible is called a *group*.

Example The collection of bijections from a set to itself is a group with respect to composition.

Definition 1.4 A map $f : G_1 \rightarrow G_2$ of monoids is a *homomorphism* if $f(g_1g_2) = f(g_1)f(g_2)$ and $f(e_1) = e_2$. If G_1, G_2 are groups, it suffices to say that $f(xy) = f(x)f(y)$.

Definition 1.5 A bijective homomorphism is called an *isomorphism*. An isomorphism from a group to itself is called an *automorphism*.

Theorem 1.6 For any group G , there is a set S and an injective homomorphism from G to the group of permutations of S .

Let $P(G)$ be the group of permutations of G and define $f : G \rightarrow P(G)$ by $f(g) = L_g$ where $L_g(x) = gx$. Note that L_g has an inverse, $L_{g^{-1}}$, and hence is a permutation. Moreover, note that

$$L_{g_1g_2}(x) = g_1g_2x = g_1L_{g_2}(x) = L_{g_1}(L_{g_2}(x))$$

so f is in fact a homomorphism. To show f is injective, we intend to show it has trivial kernel. Let $f(g) = id_G$. That is $L_g(x) = gx = x$ for any $x \in G$. In particular, if $x = e$, we see $g = e$. ■

Definition 1.7 Given a subgroup H of G , a *left coset* of H is a subset of G of the form

$$aH = \{ah : h \in H\}$$

for some $a \in G$. One can similarly define a *right coset*.

Note Any 2 left cosets of H have the same cardinality.

Exercise 1 The set of left cosets of H in G partition G .

Note the cosets cover G since $e \in H$, so for any $a \in G$, $a \in aH$. Note that if $b \in aH$, then $bH = aH$. So, by the contrapositive of this statement, the cosets are pairwise disjoint.

Definition 1.8 The number of cosets of H in G is called the *index* of G over H and is denoted by $[G : H]$.

Theorem 1.9 If H is a subgroup of G , then

$$[G : 1] = [H : 1][G : H]$$

where 1 denotes the trivial subgroup of G .

Theorem 1.10 If H is a subgroup of G , the following properties are equivalent:

- (i) $xHx^{-1} = H$ for any $x \in G$;
- (ii) $xH = Hx$ for any $x \in G$;
- (iii) The elementwise product of two right cosets is a right coset.
- (iv) H is the kernel of some group homomorphism $f : G \rightarrow G'$ for some G' .

Definition 1.11 A subgroup with any of the above properties is said to be *normal*.

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Let us now prove the above theorem.

(i) \Rightarrow (ii) This implication follows directly from the definition of these sets.

(ii) \Rightarrow (iii) We have

$$(Hx)(Hy) = H(xH)y = H(Hx)y = (HH)xy = Hxy$$

(iii) \Rightarrow (iv) By (iii), $HxHy = Hz$ for some $z \in G$. So the cosets Hxy and Hx have an element $xy = hz$ in common. So $Hxy = Hz$.

(iv) \Rightarrow (i) Let f be the homomorphism given by (iv). Notice that for $h \in H$, $f(hxh^{-1}) = e$, so $xHx^{-1} \subseteq \ker(f) = H$. Similarly, $H \subseteq xHx^{-1}$.

Definition 2.1 Let H be a subgroup of G . The *normalizer* of H is

$$N_H = \{x \in G : xHx^{-1} = H\}$$

The *centralizer* of a subset S of G is

$$\{x \in G : xhx^{-1} = h \forall h \in H\}$$

The centralizer of G itself is said to be the *center* of G , usually denoted by $Z(G)$.

Theorem 2.2 Let H, K be subgroups of G with $H \subseteq N_K$. Then

- (a) $HK = KH$;
- (b) HK is a subgroup of G ;
- (c) K is normal in HK , $H \cap K$ is normal in H , and $H/H \cap K \cong HK/K$.

(a) Since $H \subseteq N_K$, $hKh^{-1} = K$ for $h \in H$. Thus $hK = Kh$ for any $h \in H$. So for $hk \in HK$, $hk = hK = Kh \subseteq KH$. Thus $HK \subseteq KH$. Similarly, $kh \in Kh = hK \subseteq HK$.

(b) Clearly HK contains the identity since H and K do. Moreover, for some $hk \in HK$, $k^{-1}h^{-1} \in KH = HK$ and $k^{-1}h^{-1}hk = hkk^{-1}h^{-1} = e$. It remains to show that HK is closed under its operation. Note that a product of elements of HK would, a priori,

be in $HKHK$. By (a),

$$HKHK = HHKK = HK$$

- (c) Note that N_K is a group containing H and K (*the fact that N_K is a group can be proven with a simple check of the group axioms*). Hence $HK \subseteq N_K$ and thus K is normal in HK .

Let $\varphi : H \rightarrow HK/K$ be the composition of the inclusion $H \rightarrow HK$ and the projection $HK \rightarrow HK/K$. Then φ is a surjective homomorphism. Indeed, each element of HK/K is of the form $hkK = hK$. Moreover, the kernel of φ is $H \cap K$. So $H \cap K$ is normal in H and $H/H \cap K \cong HK/K$.

Lemma 2.3 If $K \subseteq H$ are subgroups of the finite group G , then

$$[G : K] = [G : H][H : K]$$

Let $\{h_i\}$ be a set of representatives of left cosets of K in H and $\{g_j\}$ be a set of representatives of the left cosets of H in G . We claim that $\{g_i h_j\}$ is a set of representatives of K in G . These cover G since

$$G = \cup g_i H = \cup g_i h_j K$$

Suppose $g_i h_j K = g_r h_s K$. Then in particular, $g_i h_j H = g_r h_s H$ and thus $g_i = g_r$, so $i = r$. Therefore, $g_i h_j K = g_i h_s K$ and thus $h_j K = h_s K$, so $j = s$. Hence, these cosets are disjoint.

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Definition 3.1 Let A be a finite set. Denote the *set of permutations* of A by S_A or $P(A)$. Given $\sigma \in S_A$ we can define an equivalence relation \sim_σ such that $a \sim_\sigma b$ if $\sigma^n(a) = b$. The equivalence classes, say B_1, \dots, B_k , of this relation are called the *orbits* of σ . For $1 \leq i \leq k$, define $\sigma_i : A \rightarrow A$ by

$$\sigma_i(x) = \begin{cases} \sigma(x) & ; x \in B_i \\ x & ; \text{otherwise} \end{cases}$$

Notice $\sigma = \sigma_1 \sigma_2 \cdots \sigma_k$ and these σ_i commute with one another.

Definition 3.2 A permutation $\sigma \in S_A$ is called a *cycle* if it has at most one orbit of cardinality greater than one. If said orbit has k elements, σ is said to be a *k-cycle*.

Definition 3.3 Two cycles are said to be *disjoint* if their orbits are disjoint.

Definition 3.4 A *transposition* is a 2-cycle.

Theorem 3.5 Every permutation can be written as a product (composition) of transpositions.

We start by introducing cycle notation. Let $(a_1 a_2 \dots a_k)$ denote the k -cycle that takes $a_i \mapsto a_{i+1}$ and $a_k \mapsto a_1$. This notation makes it clear that

$$(a_1 a_2 \dots a_k) = (a_1 a_k) \cdots (a_1 a_3)(a_1 a_2)$$

And any permutation is the product of k -cycles, we are done.

Note Let $\sigma_1 = (a_1 \dots a_k)$, $\sigma_2 = (b_1 \dots b_m)$ and $\tau = (a_i b_j)$. Without losing generality, suppose $i = j = 1$. Compute:

$$\begin{aligned} \tau\sigma_1\sigma_2 &= (a_1 b_1)(a_1 \dots a_k)(b_1 \dots b_m) \\ &= (b_1 \dots b_m a_1 \dots a_k) \end{aligned}$$

Consider $\sigma = (a_1 a_j)(a_1 \dots a_k)$. Then $\sigma = (a_1 \dots a_{j-1})(a_j a_{j+1} \dots a_k)$. So if i and j are in the same orbit of σ , then the cycles of σ are the same except that the cycle containing i and j is broken into two cycles.

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Definition 4.1 We say a permutation is *even* (resp. *odd*) if it can be written as a product of an even (resp. odd) number of transpositions.

Theorem 4.2 No permutation is both even and odd.

Definition 4.3 The group of even permutations of $\{1, \dots, n\}$ is called the *alternating group* denoted A_n .

Lemma 4.4 A_n is generated by 3-cycles.

We will consider the case where there are two 2-cycles and this can be extended to any even permutation. If the 2 cycles are disjoint,

$$(a\ b)(c\ d) = (a\ c\ b)(a\ c\ d)$$

otherwise,

$$(a\ b)(a\ c) = (a\ c\ d)$$

So any even permutation can be written as a product of pairs of transpositions and each pair can be written as a product of 3-cycles, as desired.

Lemma 4.5 If $n \geq 5$, then any two 3-cycles in S_n are conjugate by an element of A_n .

Let $\sigma_1 = (a\ b\ c)$ and $\sigma_2 = (a\ b\ c)$. Let $\gamma \in S_n$ map $a \mapsto e$, $b \mapsto f$, $c \mapsto g$. Note,

$$\gamma\sigma_1\gamma^{-1} = \gamma(a\ b\ c)\gamma^{-1} = (e\ f\ g) = \sigma_2$$

If γ is even, we are done. Otherwise, choose distinct $r, s \in \{1, 2, \dots, n\} \setminus \{a, b, c\}$. Such r, s exist since $n \geq 5$. Let $\tau = (r\ s)$. Since τ and σ are disjoint, they commute, hence

$$\begin{aligned} (\gamma\tau)\sigma_1(\gamma\tau)^{-1} &= (\gamma\tau)\sigma_1(\tau^{-1}\gamma^{-1}) \\ &= \gamma(\tau\sigma_1)\tau^{-1}\gamma^{-1} \\ &= \gamma(\sigma_1\tau)\tau^{-1}\gamma^{-1} \\ &= \gamma\sigma_1\gamma^{-1} = \sigma_2 \end{aligned}$$

and $\gamma\tau$ is even as desired.

Corollary 4.6 If a normal subgroup N of A_n contains a 3-cycle, then N contains all 3-cycles of S_n .

Theorem 4.7 A_n is simple if and only if $n \geq 5$.

The forward direction can be done ad hoc for $n < 5$.

Let N be a normal subgroup of A_n .

Case 1: N contains a 3-cycle. By the above corollary, it contains all 3-cycles, so since A_n is generated by 3-cycles, $N = A_n$. We now wish to reduce the nontrivial cases to this case. That is, we wish to show that N contains a 3-cycle in each of the following cases.

Case 2: N contains an element $\sigma = (a_1 a_2 \dots a_r)\tau$ where $r \geq 4$ and τ is a product of cycles which are disjoint from $(a_1 \dots a_r)$. Let $\delta = (a_1 a_2 a_3)$. Then $\delta^{-1} = (a_1 a_2 a_3)$. Then $\sigma^{-1}(\delta\sigma\delta^{-1}) \in N$. But

$$\begin{aligned}\sigma^{-1}(\delta\sigma\delta^{-1}) &= [\tau^{-1}(a_r \dots a_1)](a_1 a_2 a_3)[(a_1 \dots a_r)\tau](a_1 a_2 a_3) \\ &= (a_1 a_2 a_3)\end{aligned}$$

as desired.

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Case 3: N contains $\sigma = (a_1 a_2 a_3)(a_4 a_5 a_6)\tau$ where τ is a product of disjoint cycles which are disjoint from $(a_1 a_2 a_3)$ and $(a_4 a_5 a_6)$. Let $\delta = (a_1 a_2 a_4)$, so $\delta^{-1} = (a_1 a_4 a_2)$. Then, $\sigma^{-1}(\delta\sigma\delta^{-1}) \in N$. However, $\sigma^{-1}(\delta\sigma\delta^{-1}) = (a_1 a_4 a_2 a_6 a_3)$, so we are done by case 2.

Case 4: N contains $\sigma = (a_1 a_2 a_3)$ where τ is product of disjoint 2-cycles which are disjoint from $(a_1 a_2 a_3)$. Then $\sigma^2 \in N$. However, since τ is a product of disjoint 2-cycles, $\tau^2 = ()$, so

$$\sigma^2 = (a_1 a_2 a_3)^2 \tau^2 = (a_1 a_2 a_3)^2 = (a_1 a_3 a_2)$$

as desired.

Case 5: Every $\sigma \in N$ is a product of an even number of disjoint 2-cycles. Say $\sigma = (a_1 a_2)(a_3 a_4)\tau$ where τ is a product of an even number of 2-cycles which are disjoint from $(a_1 a_2)$ and $(a_3 a_4)$. If $\delta = (a_1 a_2 a_3)$, then $\sigma^{-1}(\delta\sigma\delta^{-1}) = (a_1 a_3)(a_2 a_4)$. Since $n \geq 5$, we can choose $b \in \{1, \dots, n\} \setminus \{a_1, a_2, a_3, a_4\}$. Then $\xi = (a_1 a_3 b) \in A_n$ and $\gamma = (a_1 a_3)(a_2 a_3) \in N$. Further, $\gamma(\xi\gamma\xi^{-1}) \in N$ and $\gamma(\xi\gamma\xi^{-1}) = (a_1 a_3 b)$.

Definition 5.1 A *category* \mathcal{C} is a class of objects, denoted $\text{Ob}(\mathcal{C})$, and for each $A, B \in \text{Ob}(\mathcal{C})$ a set $\text{Hom}_{\mathcal{C}}(A, B)$ of morphisms. For each $A, B, C \in \text{Ob}(\mathcal{C})$, there is a binary operation $\text{Hom}_{\mathcal{C}}(A, B) \times \text{Hom}_{\mathcal{C}}(B, C) \rightarrow \text{Hom}_{\mathcal{C}}(A, C)$ (where we write the image of (f, g) by $g \circ f$) such that

- (1) If $A \neq A'$ or $B \neq B'$, then $\text{Hom}_{\mathcal{C}}(A, B) \cap \text{Hom}_{\mathcal{C}}(A', B') = \emptyset$
- (2) The binary operation \circ is associative.
- (3) For each $A \in \text{Ob}(\mathcal{C})$, there is an element $1_A \in \text{Hom}_{\mathcal{C}}(A, A)$ such that $1_A \circ g = g$ and $f \circ 1_A = f$ for $g \in \text{Hom}_{\mathcal{C}}(B, A)$ and $f \in \text{Hom}_{\mathcal{C}}(A, B)$.

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Example Some common examples of categories.

- *Set* is the category of sets where the morphisms are maps.
- *Grp* is the category of groups with homomorphisms.
- *Ab* is the category of abelian groups with homomorphisms.
- *Rng* is category of rings category of rings with ring homomorphisms.
- *Top* is the category of topological spaces with continuous maps.
- *HTop* is the category of topological spaces whose morphisms are homotopy classes of continuous maps.

Definition 6.1 If \mathcal{C} and \mathcal{D} are categories, a *covariant functor* $F : \mathcal{C} \rightarrow \mathcal{D}$ is a map $F : \text{Ob}(\mathcal{C}) \rightarrow \text{Ob}(\mathcal{D})$ and for each $A, B \in \text{Ob}(\mathcal{C})$, we have a map $F_{AB} : \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F(A), F(B))$ such that

- (1) If $f \in \text{Hom}_{\mathcal{C}}(A, B)$ and $g \in \text{Hom}_{\mathcal{C}}(B, C)$ then $F(g \circ f) = F(g) \circ F(f)$.
- (2) $F(1_A) = 1_{F(A)}$.

Definition 6.2 A *contravariant functor* from \mathcal{C} to \mathcal{D} is a map $F : \text{Ob}(\mathcal{C}) \rightarrow \text{Ob}(\mathcal{D})$ and for each $A, B \in \text{Ob}(\mathcal{C})$, we have a map $F_{AB} : \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F(B), F(A))$ such that

- (1) If $f \in \text{Hom}_{\mathcal{C}}(A, B)$ and $g \in \text{Hom}_{\mathcal{C}}(B, C)$ then $F(g \circ f) = F(f) \circ F(g)$.
- (2) $F(1_A) = 1_{F(A)}$.

Definition 6.3 In a category \mathcal{C} , $A \in \text{Ob}(\mathcal{C})$ is said to be an *initial object* in \mathcal{C} if for each $B \in \text{Ob}(\mathcal{C})$, there is a unique morphism $f \in \text{Hom}_{\mathcal{C}}(A, B)$.

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Definition 7.1 $A \in \text{Ob}(\mathcal{C})$ is a *terminal object* in \mathcal{C} if for each $B \in \text{Ob}(\mathcal{C})$ there is a unique morphism $f \in \text{Hom}_{\mathcal{C}}(A, B)$.

Definition 7.2 Let $\{A_i\}_{i \in I}$ be a family of objects in the category \mathcal{C} . Then a product for $\{A_i\}_{i \in I}$ is an object P together with a family of morphisms $\{\pi_i \in \text{Hom}(P, A_i)\}$ such that if $\{g_i \in \text{Hom}_{\mathcal{C}}(H, A_i)\}$ is any family of morphisms, then there exists a unique $g \in \text{Hom}_{\mathcal{C}}(H, P)$ such that $\pi_i \circ g = g_i$ for every $i \in I$.

Note Given a family of objects $\{X_i\}_{i \in I}$ in \mathcal{C} , we can define a category \mathcal{D} whose objects are pairs $(A, \{a_i \in \text{Hom}_{\mathcal{C}}(A, X_i)\}_{i \in I})$. Say A with $\{a_i\}$ and B with $\{b_i\}$ are objects in this category, a morphism from the former to the latter would be completely determined by a morphism $f : A \rightarrow B$ such that $a_i = b_i \circ f$ for all i . The product of $\{X_i\}$ can be equivalently defined as the terminal object of \mathcal{D} .

Theorem 7.3 Products exists in Grp .

Let $\{A_i\}_{i \in I}$ be a family of groups and P be their Cartesian product. More precisely, an element of P is an I -tuple whose i th coordinate is an element of A_i . Denote the i th coordinate of $x \in P$ by x_i . Notice P is a group with coordinate-wise operation, that is, the i th coordinate of xy is $x_i y_i$. Let $\{\pi_i\}_{i \in I}$ be the projection maps on P , i.e $\pi_i(x) = x_i$. We claim that P with $\{\pi_i\}$ is a product of Grp . Let G be some group and $\{g_i : G \rightarrow A_i\}$ be a family of morphisms in Grp . Define $g : G \rightarrow P$ by $g(x)_i = g_i(x)$. Indeed, $\pi_i \circ g = g_i$ by definition. Moreover, g is unique since any other morphism would not have this property.

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Definition 8.1 If S is a subset of a group (respectively monoid) G , then the *subgroup* (respectively *submonoid*) of G generated by S is the intersection of all subgroups (respectively submonoids) of G containing S .

Note The submonoid of a monoid G generated by $S \subseteq G$ consists of the set of all finite products of elements of S where the empty product is the identity. Further, if G is a group, then the subgroup of G generated by S is the submonoid of G generated by $S \cup S^{-1}$ where S^{-1} is the set of inverses of S .

Note If S is a subset of a group (or monoid) G which generates G and $f : S \rightarrow H$ is a map into a group (or monoid) H , then there exists at most one homomorphism $\bar{f} : G \rightarrow H$ such that $\bar{f}|_S = f$. In short, a group (or monoid) homomorphism is completely determined by where it sends the set of generators.

Definition 8.2 Let S be a set. A *free group* on S is a group G together with a map $\lambda : S \rightarrow G$ such that if g is a map on S into a group H , then there is a unique homomorphism $\bar{g} : G \rightarrow H$ such that $\bar{g} \circ \lambda = g$.

Note We can generalize this notion to any concrete category (that is, a category whose objects are sets). A free group is simply a free object in Grp .

Definition 8.3 Let \mathcal{C} be a concrete category, X be a set, A an object in \mathcal{C} , and $i : X \rightarrow A$ a map between sets. We say A together with i is a *free object* in \mathcal{C} if for any object B in \mathcal{C} and map $f : X \rightarrow B$ between sets, there is a unique morphism $g \in \text{Hom}_{\mathcal{C}}(A, B)$ such that $g \circ i = f$.

Note This property of free objects is sometimes abbreviated by simply drawing the following diagram:

$$\begin{array}{ccc} X & \xrightarrow{i} & A \\ & \searrow f & \downarrow g \\ & & B \end{array}$$

and saying it *commutes* which in general means that all paths between two objects are equivalent.

Theorem 8.4 Free monoids exist.

Let S be a set. Define $M(S) := \{(s_1, \dots, s_n) | n \geq 0, s_i \in S\}$. $M(S)$ is a monoid with concatenation and identity $()$. We have the canonical injection $\varphi : S \rightarrow M(S)$ defined by $\varphi(s) = (s)$. Given a map f from S to some monoid H , define $\bar{f} : M(S) \rightarrow H$ by $\bar{f}(s_1, \dots, s_n) = f(s_1) \cdots f(s_n)$. One can check that the respective diagram commutes.

Theorem 8.5 Free groups exist.

Let S be a set and \bar{S} be a set disjoint from S such that there is a bijection from S to \bar{S} . Given $s \in S$, denote its image via this bijection by s^{-1} . We say an element $w \in M(S \cup \bar{S})$ is of the form

$$w = s_1^{\varepsilon_1} \dots s_k^{\varepsilon_k}$$

where $s_i \in S$ and $\varepsilon_i = \pm 1$ and we say $w' \in M(S \cup \bar{S})$ is *obtained* from w if $s_i = s_{i+1}$ and $\varepsilon_i = -\varepsilon_{i+1}$ and

$$w' = s_1^{\varepsilon_1} \dots s_{i-1}^{\varepsilon_{i-1}} s_{i+2}^{\varepsilon_{i+2}} \dots s_k^{\varepsilon_k}$$

We call this process elementary reduction and we say w is a *reduced word* if $s_i = s_{i+1}$ implies $\varepsilon_i = \varepsilon_{i+1}$ for all i .

Define an equivalence relation \sim by $w \sim w'$ meaning there is a sequence of words in $M(S \cup \bar{S})$ $w = w_1, w_2, \dots, w_{n-1}, w_n = w'$ such that either w_i is obtained from w_{i+1} for all i or w_{i+1} is obtained from w_i for all i . This is indeed an equivalence relation on $M(S \cup \bar{S})$. Moreover, if $w_1 \sim w'_1$ and $w_2 \sim w'_2$, then $w_1 w_2 \sim w'_1 w'_2$. Hence the multiplication (concatenation) on $M(S \cup \bar{S})$ induces multiplication on $M(S \cup \bar{S})/\sim$ and $M(S \cup \bar{S})/\sim$ is a group. So far, we have the following sequence of maps:

$$S \longrightarrow S \cup \bar{S} \longrightarrow M(S \cup \bar{S}) \longrightarrow M(S \cup \bar{S})/\sim$$

Suppose we are given a map $f : S \rightarrow H$ for some group H . Define $f' : S \cup \bar{S} \rightarrow H$ by $f'(s^{\pm 1}) = f(s)^{\pm 1}$. Let $f'' : M(S \cup \bar{S}) \rightarrow H$ be the unique map given by $M(S \cup \bar{S})$ being the free monoid on $S \cup \bar{S}$ and let g be the map induced by f'' on $M(S \cup \bar{S})/\sim$. One can check that the following diagram commutes:

$$\begin{array}{ccccccc}
 S & \longrightarrow & S \cup \overline{S} & \longrightarrow & M(S \cup \overline{S}) & \longrightarrow & M(S \cup \overline{S}) / \sim \\
 & & & & \downarrow f'' & & \\
 & \searrow f & & \searrow f' & & & \\
 & & & & H & \xleftarrow{g} &
 \end{array}$$

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Note We've shown that a free group is a set equivalence classes $M(S \cup \overline{S}) / \sim$

Theorem 9.1 Each equivalence class of $M(X \cup \overline{X}) / \sim$ contains a unique reduced word.

Let S be the set of reduced words in $M(S \cup \overline{S})$ and $P(S)$ be the set of permutations of S .