Topology I

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Contents

1   Preliminaries from Group Theory

Free groups   usually do not appear in the beginner courses even though they are fundamental objects in group theory. E.g. every group is a quotient of a free group. They play an important role in geometric group theory or (low-dimensional) topology. They can be constructed as *free products* (of copies of $\mathbb{Z}$), an equally fundamental construction.

1.1   The free product of groups

Intuitively, the free product of a family of groups is the "largest group generated by them". As many basic constructions in algebra or topology, it can be elegantly characterized by a *universal property*, namely as the coproduct in the category of groups.

Definition 1.1. The *free product* of a family of groups G_ι, $\iota \in I$, is a group G together with a family of group homomorphisms $\varphi_\iota : G_\iota \to G$ such that the following universal property holds:

$$
\begin{array}{ccc}
G_\iota & \xrightarrow{\ \varphi_\iota\ } & G \\
 & \searrow{\scriptstyle \psi_\iota} & \ \big\downarrow{\scriptstyle \exists! \psi} \\
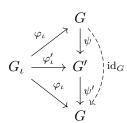 & & H
\end{array}
$$

For every family of homomorphisms $\psi_\iota : G_\iota \to H$ into some group H, there exists a unique group homomorphism $\psi : G \to H$ such that $\psi_\iota = \psi \circ \varphi_\iota$ for all $\iota \in I$.

Notation   The free product will be denoted as $\ast_{\iota \in I} G_\iota$, or $G_1 \ast \ldots \ast G_n$ in the finite case.

The *uniqueness* of the free product of groups up to (unique) isomorphism follows from general arguments (sometimes referred to as *general* or *abstract nonsense*), independent of the category (applying to the coproduct in any category):

Consider two free products $(\varphi_\iota : G_\iota \to G)_{\iota \in I}$ and $(\varphi'_\iota : G_\iota \to G')_{\iota \in I}$ of the family $(G_\iota)_{\iota \in I}$.

$$
\begin{array}{ccc}
 & & G \\
 & \nearrow{\scriptstyle \varphi_\iota} & \big\downarrow{\scriptstyle \psi} \\
G_\iota & \xrightarrow{\ \varphi'_\iota\ } & G' \quad \big| \mathrm{id}_G \\
 & \searrow{\scriptstyle \varphi_\iota} & \big\downarrow{\scriptstyle \psi'} \\
 & & G
\end{array}
$$

By the universal properties, we obtain maps ψ and ψ' as in the diagram. Applying uniqueness to the big triangle, we see that $\psi' \circ \psi$ is the *unique* map satisfying the universal property for $G \to G$. But the identity map clearly does as well, hence $\psi' \circ \psi = \mathrm{id}_G$, and in the same way one sees $\psi \circ \psi' = \mathrm{id}_{G'}$. Hence $G \cong G'$.

However, the *existence* of the free product is nontrivial (The existence of a coproduct depends on the category).

Immediate requirements   for the free product as a consequence of the universal property:

- The φ_ι are injective (i.e. embeddings), so we can think of the G_ι as subgroups of G.

- The subgroups G_ι generate G.

Thus every element in the free product has a representation as a product of the form $g_1 \cdots g_n$ with $n \in \mathbb{N}_0$ and $g_i \in G_{\iota_i} - \{1\}$ such that $\iota_i \neq \iota_{i+1}$ for all $1 \leq i \leq n-1$. This form is called *reduced*.

Not clear right away: The free product being the "largest gorup generated by its factors" should mean that the factors are "algebraically independent" in the sense that group elements have *unique representations* as reduced products.

First proof of existence   For a family of families

$$(\psi_{\iota\kappa} G_\iota \to H_\kappa)_{\iota \in I}, \quad \kappa \in K$$

the mapping problem is solved by the family of induced homomorphisms into the direct product of the groups H_κ.

$$G_\iota \xrightarrow{(\varphi_{\iota\kappa})_\kappa} \prod_{\kappa \in K} H_\kappa$$
$$\varphi_{\iota\kappa_0} \searrow \quad \downarrow \mathrm{proj}_{\kappa_0}$$
$$H_{\kappa_0}$$

To achieve uniqueness, replace $\prod_\kappa H_\kappa$ by the subgroup generated by the images of all $(\varphi_{\iota\kappa})_\kappa$. This family can be regarded as an "approximation" of the free product of the G_ι.

Now note that the universal property needs only be checked for families $(\psi_\iota : G_\iota \to H)_\iota$ whose images generate H. The equivalence classes of such families form a set, because the size of H is restricted in terms of the sizes of I and the G_ι. Apply the above-mentioned construction to a family of representatives of these equivalence classes. $\qquad\square$

This proof, while quite general, reveals very little about the structure of the free product. We now give an explicit construction of the free product, which clarifies its structure.

Second proof of existence   One can construct the free product as an abstract group with underlying set the reduced words, as defined above, and concatenation plus reduction as the group operation. However, verifying associativity is complicated due to possible cancelations.

It is simpler to onstruct the free product as a group of symmetries of a combinatorial object (as a permutation group). Take W to be the set of reduced words $(g_1, \ldots, g_n)$ with $n \in \mathbb{N}_0$, $g_i \in G_{\iota_i} - \{1\}$ and $\iota_i \neq \iota_{i+1}$ for all $1 \leq i < n$. For every $\iota \in I$, define an action of G_ι on W by defining $g \cdot (g_1, \ldots, g_n)$ as the reduction of the word $(g, g_1, \ldots, g_n)$. It is easy to see that this is indeed an action.

These actions are clearly faithful (effective), even free[1], and yield embeddings $\varphi_\iota : G_\iota \hookrightarrow S(W)$ into the symmetric group of W. Take $G < S(W)$ to be the subgroup generated by the images of the φ_ι. Observe that for the action G on W it holds that $(g_1 \cdots g_n) \cdot () = (g_1 \cdots g_n)$ for a reduced product in G. This shows that different reduced products act by different permutations of W, and therefore are different group elements. In other words, the elements in G have *unique* representations as reduced products. In this sense, the G_i are "algebraically independent".

The universal property is now a direct consequence of the uniqueness of reduced product representations. With the notation as in definition 1.1, the only possibility to define ψ on reduced words is as $\psi(g_1 \cdots g_n) := \prod_{i=1}^n \psi_{\iota_i}(g_i)$, where $g_i \in G_{\iota_i}$. By the uniquenss of reduced representations, this is well-defined and clearly makes the necessary diagram commute. It remains to see that the map ψ is multiplicative and hence a group homomorphism.

Let $g_1 \cdots g_n$ and $g'_k \cdots g'_1 \in W$. There is a maximal index m with $0 \leq m \leq n, k$ s.t. $\iota'_j = \iota_j$ and $g'_j g_j = 1$ for $1 \leq j \leq m$. Then either the product $g'_k \cdots g'_{m+1} g_{m+1} \cdots g_n$ obtained from the full unreduced product by m cancellations is reduced (i.e. $\iota'_{m+1} \neq \iota_{m+1}$ or $m = \min(n, k)$), or

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[1]faithful = nontrivial elements act nontrivially, full = nontrivial elements have no fixed points

$m < \min(n,k)$ and $\iota'_{m+1} = \iota_{m+1}$, $g'_{m+1}g_{m+1} \neq 1$, in which case $g'_k \cdots (g'_{m+1}g_{m+1}) \cdots g_n$ is reduced. In both cases, multiplicativity is clear. □

Remark 1.2. The action of G on W is simply transitive, because the empty word has trivial stabilizer and point stabilizers along orbits are conjugate to each other. It extends to an action of G on a coloured graph with vertices W. To construct it, connect $()$ to (g) for $g \in G_\iota - \{1\}$ by an edge of colour ι. Extend this in a G-invariant way by connecting $(g_1, \ldots, g_n)$ to $(g_1, \ldots, g_{n-1}, g)$ with $g \in G_{\iota_n} - \{1, g_n\}$, and $(g_1, \ldots, g_{n-1})$ by edges of colour ι_n, and to $(g_1, \ldots, g_n, g)$ for all $g \in G_\iota - \{1\}$, $\iota \neq \iota_n$ by an edge of colour ι.

This homogeneous graph is in general not a tree, but it has tree-like structure, since vertices disconnect, e.g. when removing the empty word, the connected components correspond to the factors G_ι, determined by the colour" of the first letter of their vertices.

Note that in general, G is *not* the full group of symmetries of this coloured graph.

Example 1.3. Consider the free product $\mathbb{Z}/2\mathbb{Z} * \mathbb{Z}/2\mathbb{Z} \cong D_\infty = \mathrm{Isom}(\mathbb{Z})$: Let a, b be the reflections of $\mathbb{Z}$ around 0 and $\frac{1}{2}$, respectively. Send the generators of the two copies of $\mathbb{Z}/2\mathbb{Z}$ to a and b to get a surjective map $\alpha : \mathbb{Z}/2\mathbb{Z} * \mathbb{Z}/2\mathbb{Z} \to D_\infty$, which one checks to be injective by computing the images of 0 and 1.

1.2   Free Groups

Intuitively, the free group on a given set is the "largest group generated by it". It is defined via a universal property:

Definition 1.4. The *free group* on a set S is a group $F = F(S)$ together with a map $\varphi : S \to F$ such that the following universal property holds:

$$
\begin{array}{ccc}
S & \xrightarrow{\;\varphi\;} & F \\
 & {\psi}\searrow & \downarrow{\exists! \widehat{\psi}} \\
 & & H
\end{array}
$$

For any map $\psi : S \to H$ into some group H, there exists a unique group homomorphism $\widehat{\psi} : F(S) \to H$ such that $\psi = \widehat{\psi} \circ \varphi$.

In other words, the free group constitutes a left adjoint to the forgetful functor from groups to sets. As before, this defines the free group uniquely up to isomorphism(, provided it exists). The existence can be established by constructing them as free products:

Existence   Let S be a set. Consider the map $S \to *_{s \in S} \mathbb{Z}_s =: F(S)$, $s \mapsto 1_s$, where $\mathbb{Z}_s$ is a copy of $\mathbb{Z}$ indexed by s and 1_s is the unit in that copy. The universal property of free products implies that φ satisfies the universal property of a free group: A map $\psi : S \to H$ corresponds to a family of group homomorphisms $\psi_s \mathbb{Z}_s \to H$, $1_s \mapsto \psi(s)$. The universal property of free products yields a map $\widehat{\psi} : F(S) \to H$ such that $\psi_s = \widehat{\psi} \circ \varphi_s$. Restricting those maps to S shows $\psi = \widehat{\psi} \circ \varphi$, as desired. □

We also obtain the following information on the structure of free groups: $\varphi : S \to F(S)$ is injective, so we can think of S as a subset of $F(S)$, and the elements of S generate $F(S)$. By our analysis of free products, the elements in $F(S)$ have *unique reduced normal forms* $s_1^{n_1} \cdots s_k^{n_k}$ with $s_i \in S$, $n_i \in \mathbb{Z} - \{0\}$ and $s_i \neq s_{i+1}$ for $1 \leq i < k$. In this sense, the generators $s \in S$ are "algebraically independent" in $F(S)$.

The free group can be realized (and could in fact also be constructed) as the *full* group of symmetries of a combinatorial object, namely of a coloured oriented tree. Consider the graph

$G = G(S)$ with vertex set $F = F(S)$ and edges $(\gamma, \gamma s)$ for all $\gamma \in F$ and $s \in S$ with colour s, as in remark 1.2. At any point $\gamma \in F$, there will be $|S|$ edges going away and towards γ each. Left multiplication gives a natural action of F on G, which is simply transitive on vertices. One easily sees that this is the full group of symmetries (respecting orientation and colours). An (unoriented) path $\gamma_0, \gamma_1 = \gamma_0 s_1^{\varepsilon_1}, \ldots, \gamma_n = \gamma_0 s_1^{\varepsilon_1} \cdots s_n^{\varepsilon_n}$ is "locally embedded" in the sense that $\gamma_{i-1} \neq \gamma_{i+1}$ for all $1 \leq i \leq n - 1$ if and only if $s_i^{\varepsilon_i} s_{i+1}^{\varepsilon_{i+1}}$, and in this case $s_1^{\varepsilon_1} \cdots s_n^{\varepsilon_n}$ is a reduced product (i.e. no cancellations can occur). The uniqueness of reduced product representations in the free group implies that there are no cycles in the graph G, i.e. G is indeed a tree.

Remark 1.5. This gives an alternate geometric way of proving the existence of free groups: First construct the tree (either inductively or via covering theory as the universal cover of a bouquet of circles), then look at its automorphism group and prove that it satisfies the universal property. We will come back to this later.

Next we will define the *rank* of a free group by abelianizing it. We recall that the *abelianization* of a group G is the left adjoint of the inclusion from abelian groups to groups, obtained by dividing out its commutator subgroup $G^{\mathrm{ab}} := G/[G, G]$, thereby introducing commutation relations between all elements. It is the largest abelian quotient of G.

Abelianizing the free group $F(S)$ on a set S yields the free abelian group with basis S, $F^{\mathrm{ab}}(S) = \bigoplus_{s \in S} \mathbb{Z}_s$. We will think of elements of this direct sum as finite sums $\sum_{s \in S} m_s s$. Indeed, the homomorphism $\ast \mathbb{Z}_s \to \bigoplus \mathbb{Z}_s$ defined by $1_s \mapsto s$, i.e. $s_1^{m_1} \cdots s_n^{m_n} \mapsto \sum m_i s_i$ descends to an isomorphism $F(S)^{\mathrm{ab}} \to F^{\mathrm{ab}}(S)$, whose inverse is given by $\sum m_i s_i \mapsto [s_1^{m_1} \cdots s_n^{m_n}]$.

We know that the rank free abelian groups is well-defined as the size of a basis. Therefore, the following definition yields a well-defined invariant of free groups:

Definition 1.6. The rank of a free group on a set S is defined to be the cardinality $|S|$.

1.3   Group Presentations

A presentation of a group is a description in terms of generators and relations. Presentations always exist, but they are highly non-unique and in general it is difficult to derive actual information about the group from them.

Every group Γ is a quotient of a free group: Take $S \subseteq \Gamma$ to be a generating set of Γ. Then the morphism $f : F(S) \twoheadrightarrow \Gamma$ extending id_S is surjective. In other words, f is the map that sends a word in the $s_i \in S$ to its product evaluated in Γ. An element $r = s_1^{m_1} \cdots s_n^{m_n} \in \ker f$ is called a *relation* between the generators in S. It corresponds to an equation $f(r) = s_1^{m_1} \cdots s_n^{m_n} = 1$ in Γ. Hence the free group provides a natural space for parametrizing possible relations between the elements of S in Γ.

If $R \subseteq \ker f \lhd F(S)$ is a set of relations, then an element r' in the normal subgroup $N(R) \lhd F(S)$ generated by R is called a *consequence* of the relations in R, since the equation in Γ corresponding to r' can be algebraically deduced from the equations corresponding to R. A set $R \subseteq \ker f$ of relations which generates $\ker f$ as a normal subgroup of $F(S)$ is called a *complete* set of relations for Γ. The homomorphism f then descends to the isomorphism $F(S)/N(R) \xrightarrow{\cong} \Gamma$.

This gives a description of Γ in terms of generators $S \subseteq \Gamma$ and relations $R \subseteq F(S)$ called a presentation.

Definition 1.7. For sets S and $R \subseteq F(S)$ define the group $\langle S \mid R \rangle := F(S)/N(R)$ *presented* by generators S and relations R. Given a group Γ, an isomorphism $\Gamma \cong \langle S \mid R \rangle$ for S, R as above is called a *presentation* of Γ.

A group admitting a presentation with finitely many generators and relations is called *finitely presented.*

Every group admits many different presentations. Unfortunately, some basic questions are often hard or impossible to answer, e.g. it is undecidable whether two given presentations describe the same group, or even whether a given presentation describes the trivial group. Also, given a presentation and a word in the generators, it is undecidable in general whether the corresponding group element is trivial.

Example 1.8. (i) $F(S) = \langle S \mid \emptyset \rangle$.

(ii) $\langle S_1 \mid R_1 \rangle * \langle S_2 \mid R_2 \rangle \cong \langle S_1 \sqcup S_2 \mid R_1 \sqcup R_2 \rangle =: G$ canonically: For $i = 1, 2$ we have a morphism $F(S_i) \to G$ by the universal property, which sends R_i to 1. Hence we get morphisms $\varphi_i : \langle S_i \mid R_i \rangle \to G$ by the universal property of quotients.

Let $\psi_i : \langle S_i \mid R_i \rangle \to H$ be some morphisms. Similarly to before, let $F(S_1 \sqcup S_2) \to H$ be defined as $s_i \mapsto \psi_i(s_i)$ for $s_i \in S_i$. Again this map sends $R_i \mapsto 1$, so it descends to a morphism $G \to H$. Since we had no choice in the definition of this map, it is unique. (This gives an alternative way of proving the existence of free products, based on the existence of free groups).

(iii) There is a canonical isomorphism $\langle S \mid R \cup R' \rangle \cong \langle S \mid R \rangle / N(\pi(R'))$, where $\pi : F(S) \to \langle S \mid R \rangle$ is the natural quotient map: Both morphisms $F(S) \to \langle S \mid R_1 \cup R_2 \rangle, \langle S \mid R \rangle / N(\pi(R'))$ send $R \cup R'$ to 1, so we get induced morphisms in both directions which are clearly inverse to each other.

(iv) $\langle S \mid R \rangle^{\mathrm{ab}} \cong \langle S \mid R \cup \{[s_1, s_2] \in F(S) \mid s_1, s_2 \in S\} \rangle$ by (iii).

(v) $\mathbb{Z}/n\mathbb{Z} \cong \langle a \mid a^n \rangle$

(vi) $\mathbb{Z}^2 \cong \langle a, b \mid [a, b] \rangle$

(vii) $D_n \cong \langle a, b \mid a^n, b^2, baba \rangle =: \Gamma$ where a represents a rotation by $\frac{2\pi}{n}$, and b a reflection: Indeed, by universal properties we get a surjective map $\Gamma \to D_n$. In Γ it holds that $ba^k = a^{-k}b$, so every element can be written as $a^i b^j$ with $0 \le i < n$ and $0 \le j < 2$, i.e. $|\Gamma| \le 2n$.

1.4   Free products with amalgamations

With regard to the Seifert-van Kampen theorem for fundamental groups we discuss a generalization of the free product of (two) groups. Consider two group homomorphisms $\alpha_i : H \to G_i$. We want to construct the "largest group generated by G_1 and G_2 where G_1 and G_2 are amalgamated along H", meaning that $\alpha_1(H) \subseteq G_1$ and $\alpha_2(H) \subseteq G_2$ should be identified. More precisely, we have a universal property. By a solution of (α_1, α_2) we mean an extension to a commutative diagram

$$
\begin{array}{ccc}
G & \xrightarrow{\varphi_1} & K \\
\alpha_1 \uparrow & & \uparrow \varphi_2 \\
H & \xrightarrow{\alpha_2} & G_2
\end{array}
$$

Definition 1.9. The amalgamated product (or pushout, or fibered coproduct) $G_1 *_{(H,\alpha_1,\alpha_2)} G_2 = G_1 *_H G_2$ of α_1, α_2 is a solution $(K, \varphi_1, \varphi_2)$ such that for every solution (K', ψ_1, ψ_2) there exists a unique morphism $\psi : K \to K'$ such that $\psi_i = \psi \circ \varphi_i$.

If $H = 1$, this is exactly the free product. In general, the free product with amalgamation can easily be constructed using presentations (see exercise).

2   Fundamental Group and Covering Spaces

2.1   Homotopy

Definition 2.1. Let $f, g : X \to Y$ be continuous maps of topologial spaces. A *homotopy* from f to g is a continuous map $H : X \times [0, 1] \to Y$ s.t. $H(-, 0) = f$ and $H(-, 1) = g$. If $A \subseteq X$ is a subspace and $f|_A = g|_A$, then a homotopy H is called a homotopy from f to g *relative* A, if in addition it is stationary on A, i.e. $H(a, -)$ is constant for all $a \in A$. If a homotopy (relative to A) exists, the maps f, g are called *homotopic* (relative to A), write $f \simeq g$ (or $f \simeq_A g$).

We may think of a homotopy as a "continuous deformation" of maps in the sense that it connecets $f = f_0$ and $g = f_1$ by the "continuous family" of maps $f_t = H(-, t)$.

Remark 2.2.   (i) Compositions of homotopic maps are homotopic: Let $f_0 \simeq f_1 : X \to Y$ and $g_0 \simeq g_1 : Y \to Z$. Then $g_0 \circ f_0 \simeq g_1 \circ f_1$. (Exercise)

(ii) Being homotopic is an equivalence relation on the set of continuous maps $X \to Y$: Reflexivity is clear, for symmetry take $H^- : x, t \mapsto H(x, 1 - t)$. Let $f \simeq g \simeq h : X \to Y$ be homotopic, with homotopies H_1 and H_2, respectively. Then

$$H : X \times [0, 1] \to Y, \qquad (x, t) \mapsto \begin{cases} H(x, 2t) & \text{if } t \leq \frac{1}{2}, \\ H(x, 2t - 1) & \text{otherwise.} \end{cases}$$

is a homotopy from f to h. The equivalence classes are called *homotopy classes*.

Definition 2.3. Continuous maps homotopic to a constant map are called *nullhomotopic*.

Remark 2.4. A map $X \to Y$ is nullhomotopic if and only if it continuously extends to the cone $CX := X \times [0, 1]/X \times \{1\}$ of X. For example, if $X = S^n$, then $CX \cong D^{n+1}$

Definition 2.5. A continuous map $f : X \to Y$ is called a *homotopy equivalence* if there exists a *homotopy inverse*, i.e. a map $g : Y \to X$ such that $f \circ g \simeq \mathrm{id}_Y$ and $g \circ f \simeq \mathrm{id}_X$. Two topological spaces X, Y are *homotopy equivalent* if there exists a homotopy equivalence $X \to Y$, write $X \simeq Y$.

Remark 2.6.   (i) Being homotopy equivalent is an equivalence relation on topological spaces by remark 2.2. Equivalence classes are called *homotopy types*.

(ii) Homeomorphisms are homotopy equivalences.

Definition 2.7. A topological space is *contractible* if it is homotopy equivalent to "the" point. Equivalently, id_X is nullhomotopic.

Example 2.8. If $W \subseteq \mathbb{R}^n$ is star-shaped relative to $w_0 \in W$ (that is, for every $w \in W$, the line segment connecting w_0 and w lies completely in W), then id_W is homotopic to the constant map c_{w_0} with value w_0 via the homotopy $H(w, t) = (1 - t)w + tw_0$. Hence W is contractible.

Definition 2.9. A *retraction* of a topological space X onto a subspace $A \subseteq X$ is a continuous map $r : X \to A$ with $r|_A = \mathrm{id}_A$. Equivalently, it is a continuous map $r : X \to X$ with $r \circ r = r$ and $r(X) = A$.

Retractions are the topological version of projections. Intuitively, a topological space is topologically "at least as complicated" as any of its retracts. A retract is a sbuspace whose position inside the ambient space is "as simple as possible".

Definition 2.10. A (strong) *deformation retraction* of a topological space X onto a subspace $A \subseteq X$ is a homotopy relative A from id_X to a retraction onto A. In this case, one calls A a (strong) deformation retract of X.

Note that if a retraction is (the final map of) a deformation retraction, then it is a homotopy inverse to the inclusion $A \hookrightarrow X$, in particular a homotopy equivalence.

Remark 2.11.   (i) If X (strongly) deformation retracts to a point, then X is contractible. Note that the converse fails, see exercises.

 (ii) Consider the punctured disk $D^n \setminus \{0\}$. It (strongly) deformation retracts to $\partial D^n = S^{n-1}$. We will see later that D^n does not deformation retract to its boundary.

 (iii) The mapping cylinder M_f of a continuous map $f : X \to X$,

$$M_f := (X \times [0, 1] \sqcup Y)/((x, 1) \sim f(x))$$

naturally deformation retracts to Y.

2.2   Homotopy of Paths and the Fundamental Group

A *path* in a topological space X is a continuous map from an interval into X. We call a path $\gamma : [a, b] \to X$ a path from $\gamma(a)$ to $\gamma(b)$. We will now consider paths parametrized by $I = [0, 1]$.

Two paths $\gamma_0, \gamma_1 : I \to X$ from x to y are called homotopic if as maps they are homotopic relative to ∂I, i.e. if there eists a continuous map $H : I \times I \to X$ such that $\gamma_0 = H(-, 0)$, $\gamma_1 = H(-, 1)$, $H(0, -) = x$ and $H(1, -) = y$. Homotopy of paths is an equivalence relation (as above).