

# Algebraic Topology Miscellaneous Notes

Simon Xiang

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Miscellaneous notes for the Fall 2020 graduate section of Algebraic Topology (Math 380C) at UT Austin, taught by Dr. Allcock. The course was loaded with pictures and fancy diagrams, so I didn't  $\text{\TeX}$  any notes for the lectures themselves. However, I did take some miscellaneous supplementary notes, here they are. Source files: [https://git.simonxiang.xyz/math\\_notes/files.html](https://git.simonxiang.xyz/math_notes/files.html)

## Contents

1	Category Theory	2
1.1	Motivation	2
1.2	Categories	2
1.3	Special objects in categories	4
1.4	Monic and epic maps (todo)	4
1.5	Functors	4
1.6	Homotopy Categories and Homotopy Equivalence	5
1.7	Natural Transformations	5
1.8	The Yoneda lemma (todo)	7
1.9	Limits and colimits (todo)	7
2	Free Groups and Group Theory	8
2.1	Words and Reduced Words	8
2.2	Free Groups	8
2.3	Homomorphisms of Free Groups	9
2.4	Free Products of Groups	9
2.5	Group Presentations	10
2.6	Free Abelian Groups (todo)	10
2.7	Semidirect products and Commutators(todo)	10
3	Van Kampen's Theorem	12
3.1	The van Kampen Theorem (Hatcher)	12
3.2	The van Kampen Theorem (Lee)	12
3.3	The fundamental groupoid	13

## §1 Category Theory

Today we talk about abstract nonsense! These notes will follow Evan Chen's Napkin §60 and May's "A Concise Course in Algebraic Topology" §2.

### §1.1 Motivation

Why do we talk about categories? Categories rise from objects (sets, groups, topologies) and maps between them (bijections, isomorphisms, homeomorphisms). Algebraic topology speaks of maps from topologies to groups, which makes maps between categories a suitable tool for us.

**Example 1.1.** Here are some examples of morphisms between objects:

- A bijective homomorphism between two groups  $G$  and  $H$  is an isomorphism. What also works is two group homomorphisms  $\phi: G \rightarrow H$  and  $\psi: H \rightarrow G$  which are mutual inverses, that is  $\phi \circ \psi = \text{id}_H$  and  $\psi \circ \phi = \text{id}_G$ .
- Metric (or topological) spaces  $X$  and  $Y$  are isomorphic if there exists a continuous bijection  $f: X \rightarrow Y$  such that  $f^{-1}$  is also continuous.
- Vector spaces  $V$  and  $W$  are isomorphic if there is a bijection  $T: V \rightarrow W$  that's a linear map (aka,  $T$  and  $T^{-1}$  are linear maps).
- Rings  $R$  and  $S$  are isomorphic if there is a bijective ring homomorphism  $\phi$  (or two mutually inverse ring homomorphisms).

### §1.2 Categories

**Definition 1.1** (Category). A *category*  $\mathcal{A}$  consists of

- A class of *objects*, denoted  $\text{obj}(\mathcal{A})$ .
- For any two objects  $A_1, A_2 \in \text{obj}(\mathcal{A})$ , a class of *arrows* (also called *morphisms* or *maps* between them). Let's denote the set of arrows by  $\text{Hom}_{\mathcal{A}}(A_1, A_2)$ .
- For any  $A_1, A_2, A_3 \in \text{obj}(\mathcal{A})$ , if  $f: A_1 \rightarrow A_2$  is an arrow and  $g: A_2 \rightarrow A_3$  is an arrow, we can compose the two arrows to get  $h = g \circ f: A_1 \rightarrow A_3$  an arrow, represented in the *commutative diagram* below:

$$\begin{array}{ccc} A_1 & \xrightarrow{f} & A_2 \\ & \searrow h & \downarrow g \\ & & A_3 \end{array}$$

The composition operation can be denoted as a function

$$\circ: \text{Hom}_{\mathcal{A}}(A_2, A_3) \times \text{Hom}_{\mathcal{A}}(A_1, A_2) \rightarrow \text{Hom}_{\mathcal{A}}(A_1, A_3)$$

for any three objects  $A_1, A_2, A_3$ . Composition must be associative, that is,  $h \circ (g \circ f) = (h \circ g) \circ f$ . In the diagram above, we say  $h$  *factors through*  $A_2$ .

- Every object  $A \in \text{obj}_{\mathcal{A}}$  has a special *identity arrow*  $\text{id}_A$ . The identity arrow has the expected properties  $\text{id}_A \circ f = f$  and  $f \circ \text{id}_A = f$ .

**Note.** We can't use the word "set" to describe the class of objects because of some weird logic thing (there is no set of all sets). But you can think of a class as a set.

From now on,  $A \in \mathcal{A}$  is the same as  $A \in \text{obj}(\mathcal{A})$ . A category is *small* if it has a set of objects, and *locally small* if  $\text{Hom}_{\mathcal{A}}(A_1, A_2)$  is a set for any  $A_1, A_2 \in \mathcal{A}$ .

**Example 1.2** (Basic Categories). Here are some basic examples of categories:

- We have the category of groups  $\text{Grp}$ .
  - The objects of  $\text{Grp}$  are groups.
  - The arrows of  $\text{Grp}$  are group homomorphisms.
  - The composition of  $\text{Grp}$  is function composition.
- Describe the category  $\text{CRing}$  (of commutative rings) in a similar way.
- Consider the category  $\text{Top}$  of topological spaces, whose arrows are continuous maps between spaces.

- Also consider the category  $\text{Top}_*$  of topological spaces with a distinguished basepoint, that is, a pair  $(X, x_0)$ ,  $x_0 \in X$ . Arrows are continuous maps  $f: X \rightarrow Y$  with  $f(x_0) = y_0$ .
- Similarly, the category of (possibly infinite-dimensional) vector spaces over a field  $k$   $\text{Vect}_k$  has linear maps for arrows. There is even a category  $\text{FVect}_k$  of finite-dimensional vector spaces.
- Finally, we have a category  $\text{Set}$  of sets, arrows denote any map between sets.

**Definition 1.2** (Isomorphism). An arrow  $A_1 \xrightarrow{f} A_2$  is an *isomorphism* if there exists  $A_2 \xrightarrow{g} A_1$  such that  $f \circ g = \text{id}_{A_2}$  and  $g \circ f = \text{id}_{A_1}$ . We say  $A_1$  and  $A_2$  are *isomorphic*, denoted  $A_1 \cong A_2$ .

**Remark 1.1.** In the category  $\text{Set}$ ,  $X \cong Y \iff |X| = |Y|$ .

In other fields, we can tell a lot about the structure of an object by looking at maps between them. In category theory, we *only* look arrows, and ignore what the objects themselves are.

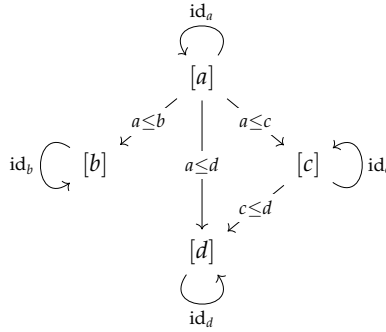
**Example 1.3** (Posets are Categories). Let  $\mathcal{P}$  be a poset. Then we can construct a category  $\mathcal{P}$  for it as follows:

- The objects of  $\mathcal{P}$  are elements of  $\mathcal{P}$ .
- We define the arrows of  $\mathcal{P}$  as follows:
  - For every object  $p \in \mathcal{P}$ , we add an identity arrow  $\text{id}_p$ , and
  - For any pair of distinct objects  $p \leq q$ , we add a single arrow  $p \rightarrow q$ .

There are no other arrows.

- We compose arrows in the only way possible, examining the order of the first and last object.

Here's a figure depicting the category of a poset  $\mathcal{P}$  on four objects  $\{a, b, c, d\}$  with  $a \leq b$  and  $a \leq c \leq d$ .



Note that no two distinct objects of a poset are isomorphic.

This shows that categories don't have to refer to just structure preserving maps between sets (these are called "concrete categories").

**Example 1.4** (Groups as a category with one object). A group  $G$  can be thought of as a category  $\mathcal{G}$  with one object  $*$ , all of whose arrows are isomorphisms.

If the universe were structured differently and kids learned category theory before groups, symmetries transforming  $X$  into itself would be a natural extension of categories that transform  $X$  into other objects, a special case in which all the maps are invertible. Alas, this is not the right timeline.

**Example 1.5** (Deriving Categories). We can make categories from other categories!

- Given a category  $\mathcal{A}$ , we can construct the *opposite category*  $\mathcal{A}^{\text{op}}$ , which is the same as  $\mathcal{A}$  but with all the arrows reversed.
- Given categories  $\mathcal{A}$  and  $\mathcal{B}$ , we can construct the *product category*  $\mathcal{A} \times \mathcal{B}$  as follows: the objects are pairs  $(A, B)$  for  $A \in \mathcal{A}$ ,  $B \in \mathcal{B}$ , and the arrows from  $(A_1, B_1)$  to  $(A_2, B_2)$  are pairs

$$\left( A_1 \xrightarrow{f} A_2, B_1 \xrightarrow{g} B_2 \right).$$

The composition is just pairwise composition, and the identity is the pair of identity functions on  $A$  and  $B$ .

### §1.3 Special objects in categories

Some categories have things called *initial objects*. For example the empty set  $\emptyset$ , the trivial group, the empty space, initial element in a poset, etc. More interestingly: the initial object of  $\mathbf{CRing}$  is the ring  $\mathbb{Z}$ .

**Definition 1.3** (Initial object). An *initial object* of  $\mathcal{A}$  is an object  $A_{\text{init}} \in \mathcal{A}$  such that for any  $A \in \mathcal{A}$  (possibly  $A = A_{\text{init}}$ ), there is exactly one arrow from  $A_{\text{init}}$  to  $A$ .

The yang to this yin is the *terminal object*:

**Definition 1.4** (Terminal object). A *terminal object* of  $\mathcal{A}$  is an object  $A_{\text{final}} \in \mathcal{A}$  such that for any  $A \in \mathcal{A}$  (possibly  $A = A_{\text{final}}$ ), there is exactly one arrow from  $A$  to  $A_{\text{final}}$ .

For example, the terminal object of  $\mathbf{Set}$  is  $\{*\}$ ,  $\mathbf{Grp}$  is  $\{1\}$ ,  $\mathbf{CRing}$  is the zero ring,  $\mathbf{Top}$  is the single point space, and a poset its maximal element (if one exists).

### §1.4 Monic and epic maps (todo)

Injectivity and surjectivity don't really make sense when talking about categories. todo

### §1.5 Functors

Motivation: maps between categories, objects rising from other objects.

**Example 1.6** (Basic Functors). Here are some basic examples of functors:

- Given an algebraic structure (group, field, vector space) we can take its underlying set  $S$ : this is a functor from  $\mathbf{Grp} \rightarrow \mathbf{Set}$  (or whatever you want to start with).
- If we have a set  $S$ , if we consider the vector space with basis  $S$  we get a functor  $\mathbf{Set} \rightarrow \mathbf{Vect}$ .
- Taking the power set of a set  $S$  gives a functor  $\mathbf{Set} \rightarrow \mathbf{Set}$ .
- Given a locally small category  $\mathcal{A}$ , we can take a pair of objects  $(A_1, A_2)$  and obtain a set  $\text{Hom}_{\mathcal{A}}(A_1, A_2)$ . This turns out to be a functor  $\mathcal{A}^{\text{op}} \times \mathcal{A} \rightarrow \mathbf{Set}$ .

Finally, the most important example (WRT this course):

- In algebraic topology, we build groups like  $H_1(X)$ ,  $\pi_1(X)$  associated to topological spaces. All these group constructions are functors  $\mathbf{Top} \rightarrow \mathbf{Grp}$ .

**Definition 1.5** (Functors). Let  $\mathcal{A}$  and  $\mathcal{B}$  be categories. A *functor*  $F$  takes every object of  $\mathcal{A}$  to an object of  $\mathcal{B}$ . In addition, it must take every arrow  $A_1 \xrightarrow{f} A_2$  to an arrow  $F(A_1) \xrightarrow{F(f)} F(A_2)$ . Refer to the commutative diagram:

$$\mathcal{A} \ni \begin{array}{ccc} A_1 & & \\ \downarrow f & \xrightarrow{\quad F \quad} & \\ A_2 & & \end{array} \in \mathcal{B} \begin{array}{ccc} B_1 = F(A_1) & & \\ \downarrow F(f) & & \\ B_2 = F(A_2) & & \end{array}$$

Functors also satisfy the following requirements:

- Identity arrows get sent to identity arrows, that is, for each identity arrow  $\text{id}_A$ , we have  $F(\text{id}_A) = \text{id}_{F(A)}$ .
- Functors respect composition: if  $A_1 \xrightarrow{f} A_2 \xrightarrow{g} A_3$  are arrows in  $\mathcal{A}$ , then  $F(g \circ f) = F(g) \circ F(f)$ .

More precisely, these are covariant functors. A contravariant functor  $F$  reverses the direction of arrows, so that  $F$  sends  $f: A_1 \rightarrow A_2$  to  $F(f): F(A_2) \rightarrow F(A_1)$ , and satisfies  $F(g \circ f) = F(f) \circ F(g)$  instead. A category  $\mathcal{A}$  has an opposite category  $\mathcal{A}^{\text{op}}$  with the same objects and with  $\mathcal{A}^{\text{op}}(A_1, A_2) = \mathcal{A}(A_2, A_1)$ . A contravariant functor  $F: \mathcal{A} \rightarrow \mathcal{B}$  is just a covariant functor  $\mathcal{A}^{\text{op}} \rightarrow \mathcal{B}$ .

**Example 1.7.** We have already talked about *free* and *forgetful* functors in Example 1.3: the forgetful functors are functors from spaces to sets (the underlying set of a group) and free functors are from sets to spaces (the basis set forming a vector space).

- Another example of a forgetful functor is a functor  $\mathbf{CRing} \rightarrow \mathbf{Grp}$  by sending a ring  $R$  to its abelian group  $(R, +)$ .

- Another example of a free functor is a functor  $\text{Set} \rightarrow \text{Grp}$  by taking the free group generated by a set  $S$  (who would have known this is free?)

Here is a cool example: functors preserve isomorphism. If two groups are isomorphic, then they must have the same cardinality. In the language of category theory, this can be expressed as such: if  $G \cong H$  in  $\text{Grp}$  and  $U: \text{Grp} \rightarrow \text{Set}$  is the forgetful functor, then  $U(G) \cong U(H)$ . We can generalize this to *any* functor and category!

**Theorem 1.1.** *If  $A_1 \cong A_2$  are isomorphic objects in  $\mathcal{A}$  and  $F: \mathcal{A} \rightarrow \mathcal{B}$  is a functor then*

$$F(A_1) \cong F(A_2).$$

*Proof.* Let's go diagram chasing!

$$\mathcal{A} \ni \begin{array}{ccc} A_1 & & \\ \uparrow f & \xrightarrow{F} & \\ A_2 & & \end{array} \begin{array}{c} B_1 = F(A_1) \\ \uparrow F(f) \\ B_2 = F(A_2) \end{array} \in \mathcal{B}$$

The main idea of the proof follows from the fact that functors preserve composition and the identity map.  $\square$

This is very very useful for us (people who are doing algebraic topology) because functors will preserve isomorphism between spaces (we get that homotopic spaces have isomorphic fundamental groups).

**Note.** As a meme (or not really, but it's still funny), we can construct the category  $\text{Cat}$  whose objects are categories and arrows are functors.

## §1.6 Homotopy Categories and Homotopy Equivalence

Let  $\text{Top}_*$  be the category of pointed topological spaces. Then the fundamental group gives a functor  $\text{Top}_* \rightarrow \text{Grp}$ . When we have a suitable relation of homotopy between maps in a category  $\mathcal{C}$ , we define the homotopy category  $\text{Ho}(\mathcal{C})$  to be the category sharing the same objects as  $\mathcal{C}$ , but morphisms the homotopy classes of maps. On  $\text{Top}_*$ , we require homotopies to map basepoint to basepoint, and we get the homotopy category  $\text{hTop}_*$  of pointed spaces.

Homotopy equivalences in  $\mathcal{C}$  are isomorphisms in  $\text{Ho}(\mathcal{C})$ . More concretely, recall that a map  $f: X \rightarrow Y$  is a homotopy equivalence if there is a map  $g: Y \rightarrow X$  such that both  $g \circ f \simeq \text{id}_X$  and  $f \circ g \simeq \text{id}_Y$ . In the language of category theory, we can obtain the analogous notion of a pointed homotopy equivalence. Functors carry isomorphisms to isomorphisms, so then the pointed homotopy equivalence will induce an isomorphism of fundamental groups. This also holds, but less obviously, for the category of non pointed homotopy equivalences.

**Theorem 1.2.** *If  $f: X \rightarrow Y$  is a homotopy equivalence, then*

$$f_*: \pi_1(X, x) \rightarrow \pi_1(Y, f(x))$$

*is an isomorphism for all  $x \in X$ .*

*Proof.* Let  $g: Y \rightarrow X$  be a homotopy inverse of  $f$ . By our homotopy invariance diagram, we see that the composites

$$\pi_1(X, x) \xrightarrow{f_*} \pi_1(Y, f(x)) \xrightarrow{g_*} \pi_1(X, (g \circ f)(x))$$

and

$$\pi_1(Y, y) \xrightarrow{g_*} \pi_1(X, g(y)) \xrightarrow{f_*} \pi_1(Y, (f \circ g)(y))$$

are isomorphisms determined by paths between basepoints given by chosen homotopies  $g \circ f \simeq \text{id}_X$  and  $f \circ g \simeq \text{id}_Y$ . Then in each displayed composite, the first map is a monomorphism and the second is an epimorphism. Taking  $y = f(x)$  in the second composite, we see that the second map in the first composite is an isomorphism. Therefore so is the first map, and we are done.  $\square$

A space  $X$  is said to be contractible if it is homotopy equivalent to a point.

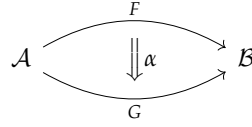
**Corollary 1.1.** *The fundamental group of a contractible space is zero.*

## §1.7 Natural Transformations

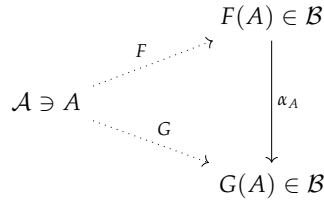
We talked about maps between objects which led to categories, and then maps between categories which lead to functors. Now let's talk about maps between functors, the natural transformation: this is actually not too strange (recall the homotopy, a "deformation" from a map to another map).

In this case, we also want to pull a map (functor)  $F$  to another map  $G$  by composing a bunch of arrows in the target space  $\mathcal{B}$ .

**Definition 1.6** (Natural Transformations). Let  $F, G: \mathcal{A} \rightarrow \mathcal{B}$  be two functors. A *natural transformation*  $\alpha: F \rightarrow G$  denoted



consists of, for each  $A \in \mathcal{A}$  an arrow  $\alpha_A \in \text{Hom}_{\mathcal{B}}(F(A), G(A))$ , which is called the component of  $\alpha$  at  $A$ . Pictorially, it looks like this:

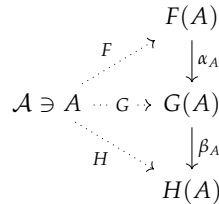


The  $\alpha_A$  are subject to the “naturality” requirement such that for any  $A_1 \xrightarrow{f} A_2$ , the following diagram commutes:

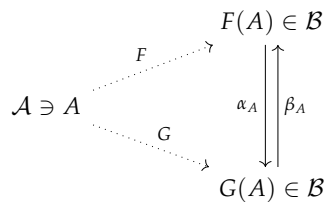
$$\begin{array}{ccc} F(A_1) & \xrightarrow{F(f)} & F(A_2) \\ \alpha_{A_1} \downarrow & & \downarrow \alpha_{A_2} \\ G(A_1) & \xrightarrow{G(f)} & G(A_2) \end{array}$$

The arrow  $\alpha_A$  represents the path that  $F(A)$  takes to get to  $G(A)$  (like in a homotopy from  $f$  to  $g$  the point  $f(t)$  gets deformed to the point  $g(t)$  continuously). Think of  $f$  representing the homotopy and the basepoints being  $F(A_1), G(A_1)$  to  $F(A_2), G(A_2)$ .

Natural transformations can be composed. Take two natural transformations  $\alpha: F \rightarrow G$  and  $\beta: G \rightarrow H$ . Consider the following commutative diagram:



We can also construct inverses: suppose  $\alpha$  is a natural transformation such that  $\alpha_A$  is an isomorphism for each  $A$ . Then we construct an inverse arrow  $\beta_A$  in the following way:



We say  $\alpha$  is a *natural isomorphism*. Then  $F(A) \cong G(A)$  *naturally* in  $A$  (and  $\beta$  is an isomorphism too!) We write  $F \cong G$  to show that the functors are naturally isomorphic.

**Example 1.8.** If  $F: \text{Set} \rightarrow \text{Grp}$  is the free functor that sends a set to the free group on such set and  $U: \text{Grp} \rightarrow \text{Set}$  is the forgetful functor sending a free group to its generating set, then we have a natural inclusion of  $S \hookrightarrow UF(S)$ . The functors  $F$  and  $U$  are left and right adjoint to each other, in the sense that we have a natural isomorphism

$$\text{Grp}(F(S), A) \cong \text{Set}(S, U(A))$$

for a set  $S$  and an abelian group  $A$ . This expresses the “universal property” of free objects: a map of sets  $S \rightarrow U(A)$  extends uniquely to a homomorphism of groups  $F(S) \rightarrow A$ .

**Definition 1.7.** Two categories  $\mathcal{A}$  and  $\mathcal{B}$  are equivalent if there are functors  $F: \mathcal{A} \rightarrow \mathcal{B}$  and  $G: \mathcal{B} \rightarrow \mathcal{A}$  and natural isomorphisms  $FG \rightarrow \text{Id}$  and  $GF \rightarrow \text{Id}$ , where the  $\text{Id}$  are the respective identity functors.

### §1.8 The Yoneda lemma (todo)

**Definition 1.8** (The functor category). The *functor category* of two categories  $\mathcal{A}$  and  $\mathcal{B}$ , denoted  $[\mathcal{A}, \mathcal{B}]$  is defined as follows:

- The objects of  $[\mathcal{A}, \mathcal{B}]$  are (covariant) functors  $F: \mathcal{A} \rightarrow \mathcal{B}$ , and
- The morphisms are natural transformations  $\alpha: F \rightarrow G$ .

todo

### §1.9 Limits and colimits (todo)

todo

## §2 Free Groups and Group Theory

Not to be confused with free *abelian* groups. Whether or not we can count is uncertain, but can we even spell? These notes will follow Fraleigh §39,40 and Hatcher §1.2.



I've decided to expand this section to include any miscellaneous group theory that I may not have covered/forgot. What texts they follow will probably be at the beginning of each subsection.

### §2.1 Words and Reduced Words

Let  $A_i$  be a set of elements (not necessarily finite). We say  $A$  is an *alphabet* and think of the  $a_i \in A$  as *letters*. Symbols of the form  $a_i^n$  are *syllables* and *words* are a finite string of syllables. We denote the *empty word* 1 as the word with no syllables.

**Example 2.1.** Let  $A = \{a_1, a_2, a_3\}$ . Then

$$a_1 a_3^{-4} a_2^2 a_3, a_2^3 a_2^{-1} a_3 a_1, \text{ and } a_3^2$$

are all words (given that  $a_i^1 = a_i$ ).

We can reduce  $a_i^m a_i^n$  to  $a_i^{m+n}$  (*elementary contractions*) or replacing  $a_i^0$  by 1 (dropping something out of the word). Using a finite number of elementary contractions, we get something called a *reduced word*.

**Example 2.2.** The reduced word of  $a_2^3 a_2^{-1} a_3 a_2^2 a_1^{-7}$  is  $a_2^2 a_3 a_1^{-5}$ .

Is it obvious or not that the reduced form of a word is unique? Does it stay the same rel elementary contractions? Apparently you have to be a great mathematician to know.

### §2.2 Free Groups

Denote the set of all reduced words from our alphabet  $A$  as  $F[A]$ . We give  $F[A]$  a group structure in the natural way: for two words  $w_1$  and  $w_2$  in  $F[A]$ , let  $w_1 \cdot w_2$  be the result by string concatenation of  $w_2$  onto  $w_1$ .

**Example 2.3.** If  $w_1 = a_2^3 a_1^{-5} a_3^2$  and  $w_2 = a_3^{-2} a_1^2 a_3 a_2^{-2}$ , then  $w_1 \cdot w_2 = a_2^3 a_1^{-3} a_3 a_2^{-2}$ .

"It would seem obvious" that this indeed forms a group on the alphabet  $A$ . Man, the weather outside today is nice.

**Definition 2.1** (Free Group). The group  $F[A]$  described above is the *free group generated by  $A$* .

Sometimes we have a group  $G$  and a generating set  $A = \{a_i \mid i \in I\}$ , and we want to know whether or not  $G$  is *free* on  $\{a_i\}$ , that is,  $G$  is the free group generated by  $\{a_i\}$ .

**Definition 2.2** (Free Generators). If  $G$  is a group with a set  $A = \{a_i\}$  of generators and is isomorphic to  $F[A]$  under a map  $\phi: G \rightarrow F[A]$  such that  $\phi(a_i) = a_i$ , then  $G$  is *free on  $A$* , and the  $a_i$  are *free generators* of  $G$ . A group is *free* if it is free on some nonempty set  $A$ .

Oh you'll be free... free indeed...

**Example 2.4.**  $\mathbb{Z}$  is the free group on one generator.

I wish we would call it the "free group on  $n$  letters" as opposed to the "free group on  $n$  generators", which is lame, to be consistent with the whole "mathematicians don't know how to spell" theme.

**Example 2.5.**  $\mathbb{Z}$  is the free group on one letter.

Much better. Time for theorem spam.

**Theorem 2.1.** If  $G$  is free on  $A$  and  $B$ , then  $A$  and  $B$  have the same order, that is, any two sets of free generators of a free group have the same cardinality.

*Proof.* Refer "to the literature". ☒

**Definition 2.3** (Rank). If  $G$  is free on  $A$ , then the number of letters in  $A$  is the *rank of the free group  $G$* .

**Theorem 2.2.** Two free groups are isomorphic if and only if they have the same rank.

*Proof.* Immediate. ☒

**Theorem 2.3.** A nontrivial proper subgroup of a free group is free.

*Proof.* Back "to the literature". ☒

**Example 2.6.** Let  $F[\{x, y\}]$  be the free group on  $\{x, y\}$ . Let

$$y_k = x^k y x^{-k}$$

for  $k \geq 0$ . The  $y_k$  for  $k \geq 0$  are free generators for the subgroup of  $F[\{x, y\}]$  that they generate. So the rank of the free subgroup of a free group can be much greater than the rank of the whole group.



## §2.3 Homomorphisms of Free Groups

**Theorem 2.4.** *Let  $G$  be generated by  $A = \{a_i \mid i \in I\}$  and let  $G'$  be any group. If  $a_i'$  for  $i \in I$  are any elements in  $G'$  not necessarily distinct, then there is at most one homomorphism  $\phi: G \rightarrow G'$  such that  $\phi(a_i) = a_i'$ . If  $G$  is free on  $A$ , then there is exactly one such homomorphism.*

*Proof.* Let  $\phi$  be a homomorphism from  $G$  into  $G'$  such that  $\phi(a_i) = a_i'$ . Then any  $x \in G$  can be written as a finite product of the generators  $a_i$ , denoted

$$x = \prod_j a_{i_j}^{n_j},$$

the  $a_i$  not necessarily distinct. Since  $\phi$  is a homomorphism, we have

$$\phi(x) = \prod_j \phi(a_{i_j}^{n_j}) = \prod_j (a_{i_j}')^{n_j},$$

so a homomorphism is completely determined by its values on elements of a generating set. This shows that there is at most one homomorphism such that  $\phi(a_i) = a_i'$ .

Now suppose that  $G$  is free on  $A$ , that is,  $G = F[A]$ . For

$$x = \prod_j a_{i_j} \in G,$$

define  $\psi: G \rightarrow G'$  by

$$\psi(x) = \prod_j (a_{i_j}')^{n_j}.$$

The map is well defined, since  $F[A]$  consists precisely of reduced words. Since the rules for computation involving exponents are formally the same as those involving exponents in  $G$ , it can be seen that  $\psi(xy) = \psi(x)\psi(y)$  for any elements  $x$  and  $y$  in  $G$ , so  $\psi$  is indeed a homomorphism.  $\square$

Note that this theorem states that a group homomorphism is completely determined by its value on each element of a generating set: eg, a homomorphism of a cyclic group is completely determined by its value on any single generator.

**Corollary 2.1.** *Every group  $G'$  is a homomorphic image of a free group  $G$ .*

*Proof.* Let  $G' = \{a_i' \mid i \in I\}$ , and let  $A = \{a_i \mid i \in I\}$  be a set with the same number of elements as  $G'$ . Let  $G = F[A]$ . Then by Theorem 2.4 there exists a homomorphism  $\psi$  mapping  $G$  into  $G'$  such that  $\psi(a_i) = a_i'$ . Clearly the image of  $G$  under  $\psi$  is all of  $G'$ .  $\square$

Only the free group on one letter is abelian.

## §2.4 Free Products of Groups

**Definition 2.4** (Free Products). As a set, the free product  $*_{\alpha} G_{\alpha}$  consists of all words  $g_1 g_2 \cdots g_m$  of arbitrary finite length  $m \geq 0$ , where each letter  $g_i$  belongs to a group  $G_{\alpha_i}$  and is not the identity element of  $G_{\alpha_i}$ , and adjacent letters  $g_i$  and  $g_{i+1}$  belong to different groups  $G_{\alpha}$ , that is,  $\alpha_i \neq \alpha_{i+1}$ .

Basically, reduced words with alternating letters from different groups. The group operation is concatenation: what if the end of  $w_1$  and the beginning of  $w_2$  belong to the same  $G_{\alpha}$ ? Merge them into a syllable: what if they merge into the identity, and so the next two letters are from the same alphabet? Merge again, and repeat forever. Eventually we'll get a reduced word.

How to prove this is associative? Relate it to a subgroup of the symmetric group, it takes care of a lot of work. So we have the free product  $\mathbb{Z} * \mathbb{Z}$ , which is also free. Note that  $\mathbb{Z}_2 * \mathbb{Z}_2$  is *not* a free group: since  $a^2 = e = b^2$ , powers of  $a$  and  $b$  are not needed. So  $\mathbb{Z}_2 * \mathbb{Z}_2$  consists of the alternating words  $a, b, ab, ba, aba, bab, abab, \dots$  together with the empty word.

A basic property of the free product  $*_{\alpha} G_{\alpha}$  is that any collection of homomorphisms  $\varphi_{\alpha}: G_{\alpha} \rightarrow H$  extends uniquely to a homomorphism  $\varphi: *_{\alpha} G_{\alpha} \rightarrow H$ . Namely, the value of  $\varphi$  on a word  $g_1 \cdots g_n$  with  $g_i \in G_{\alpha_i}$  must be  $\varphi_{\alpha_1}(g_1) \cdots \varphi_{\alpha_n}(g_n)$ , and using this formula to define  $\varphi$  gives a well-defined homomorphism since the process of reducing an unreduced product in  $*_{\alpha} G_{\alpha}$  goes not affect its image under  $\varphi$ .

**Example 2.7.** For a free product  $G * H$ , the inclusions  $G \hookrightarrow G \times H$  and  $H \hookrightarrow G \times H$  induce a surjective homomorphism  $G * H \rightarrow G \times H$ .

## §2.5 Group Presentations

Apparently, I never took group theory. Let's talk about group presentations! Motivation: form a group by giving generators and having them follow certain relations. We want the group as free (free indeed) as possible on these generators.

**Example 2.8.** Suppose  $G$  has generators  $x$  and  $y$  and is free except for the relation  $xy = yx$ , or  $xyx^{-1}y^{-1} = 1$ . This makes sure  $G$  is abelian, and so  $G$  is isomorphic to  $F[\{x, y\}]$  modulo its commutator subgroup, the smallest normal subgroup containing  $xyx^{-1}y^{-1}$ . This is because any normal subgroup containing  $xyx^{-1}y^{-1}$  gives rise to an abelian factor group and thus contains the commutator subgroup (by a previous theorem).

This example illustrates what we want: let  $F[A]$  be a free group and we want a new group as free as possible, with certain equations satisfied. We can always write these equations with the RHS equal to 1, so we consider the equations to be  $r_i = 1$  for  $i \in I$ , where  $r_i \in F[A]$ . If  $r_i = 1$ , then

$$x(r_i^n)x^{-1} = 1$$

for any  $x \in F[A]$ ,  $n \in \mathbb{Z}$ . Any product of elements equal to 1 again equals 1, so any finite product of the form

$$\prod_j x_j (r_{i_j}^{n_j}) x_j^{-1}$$

where  $r_{i_j}$  need not be distinct equals 1 in the new group. It can be seen that the set of all these finite products is a normal subgroup  $R$  of  $F[A]$ . Then any group that looks like  $F[A]$  given  $r_i = 1$  also has  $r = 1$  for all  $r \in R$ . But  $F[A]/R$  looks like  $F[A]$ , except that  $R$  has been collapsed to form the identity 1. Hence the group we are after is (at least isomorphic to)  $F[A]/R$ . We can view this group as described by the generating set  $A$  and the set  $\{r_i \mid i \in I\}$ , abbreviated  $\{r_i\}$ .

**Definition 2.5** (Group Presentations). Let  $A$  be a set and  $\{r_i\} \subseteq F[A]$ . Let  $R$  be the least normal subgroup of  $F[A]$  containing the  $r_i$ . An isomorphism  $\phi$  of  $F[A]/R$  onto a group  $G$  is a *presentation* of  $G$ . The sets  $A$  and  $\{r_i\}$  give a *group presentation*. The set  $A$  is the set of *generators for the presentation* and each  $r_i$  is a *relator*. Each  $r \in R$  is a *consequence* of  $\{r_i\}$ . An equation  $r_i = 1$  is a *relation*. A *finite presentation* is one in which both  $A$  and  $\{r_i\}$  are finite sets.

Refer back to Example 2.1:  $\{x, y\}$  is our set of generators and  $xyx^{-1}y^{-1}$  is the only relator. The equation  $xyx^{-1}y^{-1} = 1$  or  $xy = yx$  is a relation—this was an example of a finite presentation.

## §2.6 Free Abelian Groups (todo)

todo

## §2.7 Semidirect products and Commutators(todo)

I had an existential crisis when Dr. Allcock said to simply observe that one group is a semidirect of another by such and such group. These notes will follow Dummitt and Foote §5.



The direct product is what you think it is: the set of  $n$ -tuples with the group operation done componentwise.

**Definition 2.6** (Commutators). Let  $G$  be a group and  $x, y \in G$ . Let  $A, B$  be nonempty subsets of  $G$ . Then

1. Define  $[x, y] = x^{-1}y^{-1}xy$  as the *commutator* of  $x$  and  $y$ .
2. Define  $[A, B] = \langle [a, b] \mid a \in A, b \in B \rangle$ , the group generated<sup>1</sup> by commutators of elements from  $A$  and  $B$ .
3. Define  $G' = [G : G] = \langle [x, y] \mid x, y \in G \rangle$ , the subgroup of  $G$  generated by commutators of elements from  $G$ , called the *commutator subgroup* of  $G$ .

The commutator of  $x$  and  $y$  is 1 iff  $x$  and  $y$  commute, hence the name.

<sup>1</sup>Generators and presentations are starting to blur the line for me...

**Proposition 2.1.** The factor group  $G/G'$  is abelian. Furthermore,  $G/G'$  is the largest abelian quotient of  $G$  in the sense that if  $H \trianglelefteq G$  and  $G/H$  is abelian, then  $G' \leq H$ . Conversely, if  $G' \leq H$ , then  $H \trianglelefteq G$  and  $G/H$  is abelian.

*Proof.* Let  $xG', yG' \in G/G'$ . Since the commutator  $[x, y] \in G'$  collapses to zero, we have

$$\begin{aligned}(xG')(yG') &= (xy)G' \\ &= (yx[x, y])G' \\ &= (yx)G' \\ &= (yG')(xG').\end{aligned}$$

So  $G/G'$  is abelian. Now suppose  $H \trianglelefteq G$  and  $G/H$  is abelian. Then for all  $x, y \in G$  we have  $(xH)(yH) = (yH)(xH)$ , so

$$\begin{aligned}1H &= (xH)(xH)^{-1}(yH)(yH)^{-1} \\ &= (xH)^{-1}(yH)^{-1}(xH)(yH) \\ &= (x^{-1}y^{-1}xy)H \\ &= [x, y] \in H,\end{aligned}$$

which implies  $[x, y] \in H$  for all  $x, y \in G$ . So  $G' \leq H$ . Conversely, if  $G' \leq H$ , then every subgroup of  $G/G'$  is normal, in particular,  $H/G' \trianglelefteq G/G'$ . We have  $H \trianglelefteq G$  by the Lattice Isomorphism Theorem, and by the Third Isomorphism Theorem, we have

$$G/H \cong (G/G')/(H/G').$$

Since  $G/H$  is isomorphic to a quotient of the abelian group  $G/G'$ ,  $G/H$  must be abelian. □

Why does this work? We mod out by the stuff we don't like: in this case, all the commutators collapse to the identity, so elements in the quotient group commute.

### §3 Van Kampen's Theorem

OK guys, let's decompose big spaces into smaller ones and compute their fundamental groups. These notes follow Hatcher §1.2, Lee §10, and May §2.7.

#### §3.1 The van Kampen Theorem (Hatcher)

Let's take a space  $X$  and say it's the union of path-connected open subsets  $A_\alpha$ , each of which contains the basepoint  $x_0 \in X$ . Then the homomorphisms  $j_\alpha: \pi_1(A_\alpha) \rightarrow \pi_1(X)$  induced by the inclusions  $A_\alpha \hookrightarrow X$  extend to a homomorphism  $\Phi: \ast_\alpha \pi_1(A_\alpha) \rightarrow \pi_1(X)$ . The van Kampen theorem will say that  $\Phi$  is often onto but in general, we can expect  $\Phi$  to have a nontrivial kernel.

For if  $i_{\alpha\beta}: \pi_1(A_\alpha \cap A_\beta) \rightarrow \pi_1(A_\alpha)$  is the homomorphism induced by the inclusion  $A_\alpha \cap A_\beta \hookrightarrow A_\alpha$  then  $j_\alpha i_{\alpha\beta} = j_\beta i_{\beta\alpha}$ , both of these compositions being induced by the inclusion  $A_\alpha \cap A_\beta \hookrightarrow X$ , so the kernel of  $\Phi$  contains all the elements of the form  $i_{\alpha\beta}(\omega) i_{\beta\alpha}(\omega)^{-1}$  for  $\omega \in \pi_1(A_\alpha \cap A_\beta)$ .

Van Kampen says under fairly broad hypotheses that this determines all of  $\Phi$ .

**Theorem 3.1.** *If  $X$  is the union of path-connected open sets  $A_\alpha$  each containing the basepoint  $x_0 \in X$  and if each intersection  $A_\alpha \cap A_\beta$  is path-connected, then the homomorphism*

$$\Phi: \ast_\alpha \pi_1(A_\alpha) \rightarrow \pi_1(X)$$

*is onto. Furthermore, if each intersection  $A_\alpha \cap A_\beta \cap A_\gamma$  is path-connected, then the kernel of  $\Phi$  is the normal subgroup  $N$  generated by all elements of the form  $i_{\alpha\beta}(\omega) i_{\beta\alpha}(\omega)^{-1}$  for  $\omega \in \pi_1(A_\alpha \cap A_\beta)$ , and hence  $\Phi$  induces an isomorphism*

$$\pi_1(X) = \ast_\alpha \pi_1(A_\alpha) / N.$$

**Example 3.1 (Wedge Sums).** I like the visual of the wedge sum but the terminology of the smash product. If only we could keep the  $\vee$  symbol ( $\vee$ ) and say we "smash the spaces together" at a point.

We define the wedge sum  $\bigvee_\alpha X_\alpha$  with basepoints  $x_\alpha \in X_\alpha$  as the disjoint union  $\coprod_\alpha X_\alpha$  with all the basepoints  $x_\alpha$  identified to a single point. If each  $x_\alpha$  is a deformation retract of an open neighborhood  $U_\alpha$  in  $X_\alpha$ , then  $X_\alpha$  is a deformation retract of its open neighborhood  $A_\alpha = X_\alpha \setminus \bigvee_{\beta \neq \alpha} U_\beta$ . The intersection of two or more distinct  $A_\alpha$ 's is  $\bigvee_\alpha U_\alpha$ , which deformation retracts to a point. Then by van Kampen's theorem,

$$\Phi: \ast_\alpha \pi_1(X_\alpha) \rightarrow \pi_1\left(\bigvee_\alpha X_\alpha\right)$$

is an isomorphism, provided each  $X_\alpha$  is path-connected, hence also each  $A_\alpha$ . Therefore for a wedge sum of circles,  $\pi_1(\bigvee_\alpha S^1_\alpha)$  is a free group, the free product of copies of  $\mathbb{Z}$ .

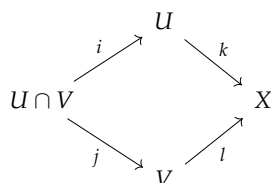


I know it always helps to see something done somewhere else. For me, the above definition fails to make any sense at all whatsoever. So, let's revisit van Kampen's from two more lenses: one from the words of Lee (*Introduction to Topological Manifolds*) and another from the categorical perspective.

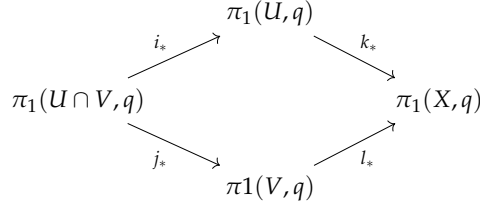
#### §3.2 The van Kampen Theorem (Lee)

Let's say we have a space  $X$  that's made up of the union of two open subsets  $U, V \subseteq X$ . We know how to compute the fundamental groups of  $U, V$ , and  $U \cap V$  (each of which is path-connected). Every loop can be written as a product of loops in  $U$  or  $V$  (visualized as the free product  $\pi_1(U) * \pi_1(V)$ ), but any loop in  $U \cap V$  only represents a single element of  $\pi_1(X)$ , even though it represents two distinct elements of the free product (one in  $\pi_1(U)$  and one in  $\pi_1(V)$ ). So  $\pi_1(X)$  can be thought of as the quotient of this free product modulo some relations from  $\pi_1(U \cap V)$  that express this redundancy.

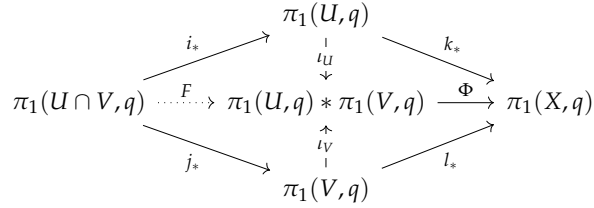
Let's do some setup so we can state a precise version of van Kampen's. Let  $X$  be a topological space and  $U, V \subseteq X$  such that  $U \cup V = X$  and  $U \cap V \neq \emptyset$ . Let  $q \in U \cap V$ . Then the four inclusion maps shown below,



induce fundamental group homomorphisms as shown below.



Now insert the free product  $\pi_1(U, q) * \pi_1(V, q)$  in the middle of the diagram and let  $\iota_U: \pi_1(U, q) \hookrightarrow \pi_1(U, q) * \pi_1(V, q)$  and  $\iota_V: \pi_1(V, q) \hookrightarrow \pi_1(U, q) * \pi_1(V, q)$  be the canonical injections. By the characteristic property (unique induced homomorphisms) of the free product,  $k_*$  and  $l_*$  induce a homomorphism  $\Phi: \pi_1(U, q) * \pi_1(V, q) \rightarrow \pi_1(X, q)$  such that the right half of the following diagram commutes:



Finally, define a map  $F: \pi_1(U \cap V, q) \rightarrow \pi_1(U, q) * \pi_1(V, q)$  by setting  $F(\gamma) = (i_*\gamma)^{-1}(j_*\gamma)^2$ . Let  $\overline{F(\pi_1(U \cap V, q))}$  denote the *normal closure*<sup>3</sup> of the image of  $F$  in  $\pi_1(U, q) * \pi_1(V, q)$ .

**Theorem 3.2** (Seifert-Van Kampen). *Let  $X$  be a topological space. Suppose  $U, V \subseteq X$  are open,  $U \cap V = X$ , and  $U, V$ , and  $U \cap V$  are path-connected. Then for any  $q \in U \cap V$ , the homomorphism  $\Phi$  is surjective, and its kernel is  $\overline{F(\pi_1(U \cap V, q))}$ . Therefore we have*

$$\pi_1(X, q) \cong \pi_1(U, q) * \pi_1(V, q) / \overline{F(\pi_1(U \cap V, q))}.$$

When the fundamental groups in question are finitely presented, the theorem has a useful reformulation in terms of generators and relations.

**Corollary 3.1.** *In addition to the hypothesis of van Kampen, assume that the fundamental groups of  $U, V$ , and  $U \cap V$  have the following finite presentations:*

$$\begin{aligned}
\pi_1(U, q) &\cong \langle \alpha_1, \dots, \alpha_m \mid \rho_1, \dots, \rho_r \rangle; \\
\pi_1(V, q) &\cong \langle \beta_1, \dots, \beta_n \mid \sigma_1, \dots, \sigma_s \rangle; \\
\pi_1(U \cap V, q) &\cong \langle \gamma_1, \dots, \gamma_p \mid \tau_1, \dots, \tau_t \rangle.
\end{aligned}$$

Then  $\pi_1(X, q)$  has the presentation

$$\pi_1(X, q) \cong \langle \alpha_1, \dots, \alpha_m, \beta_1, \dots, \beta_n \mid \rho_1, \dots, \rho_r, \sigma_1, \dots, \sigma_s, u_1 = v_1, \dots, u_p = v_p \rangle$$

where for each  $a = 1, \dots, p$ ,  $u_a$  is an expression for  $i_*\gamma_a \in \pi_1(U, q)$  in terms of the generators  $\{\alpha_1, \dots, \alpha_m\}$ , and  $v_a$  similarly expresses  $j_*\gamma_a \in \pi_1(V, q)$  in terms of  $\{\beta_1, \dots, \beta_n\}$ .

### §3.3 The fundamental groupoid

We backtrack a little to talk about categorical nonsense. This doesn't fit too well with the section on category theory, so it's here. These will follow May §2.5.



We often talk of pointed spaces, but it would be nice to talk about spaces without making such a choice. We define the fundamental groupoid  $\Pi(X)$  of a space  $X$  to be the category whose objects are the points of  $X$  and whose morphism  $x \rightarrow y$  are the equivalence classes of paths from  $x$  to  $y$ <sup>4</sup>. Then the set of endomorphisms of the object  $x$  is the fundamental group  $\pi_1(X, x)$ .

We say “groupoid” because a group is simply a groupoid with only one object (the class of morphisms or symmetries on an object). However, the category of groupoids has several objects. We also defined groupoids as categories whose morphisms are all isomorphisms. If morphisms are functors, then we have the category  $\mathbf{Grpd}$  of groupoids. So we can see  $\Pi$  as a functor  $\mathbf{Top}_* \rightarrow \mathbf{Grpd}$ .

<sup>2</sup> $F$  is not a homomorphism.

<sup>3</sup>the *normal closure* of a set means the smallest normal subgroup that contains such set.

<sup>4</sup>Recall Example 1.4 of a group being realized as a category with all its arrows isomorphisms.

Let's talk about skeletons. We have the skeleton of a category  $\mathcal{C}$  denoted by  $\text{sk}(\mathcal{C})$ . This is a "full" subcategory with one object from each isomorphism class of objects of  $\mathcal{C}$ , "full" meaning that the morphisms between two objects of  $\text{sk}(\mathcal{C})$  are all of the morphisms between these objects in  $\mathcal{C}$ . The inclusion functor  $J: \text{sk}(\mathcal{C}) \rightarrow \mathcal{C}$  is an equivalence of categories. We can find an inverse functor  $F: \mathcal{C} \rightarrow \text{sk}(\mathcal{C})$  by letting  $F(A)$  be the unique object in  $\text{sk}(\mathcal{C})$  that is isomorphic to  $A$ , choosing an isomorphism  $\alpha_A: A \rightarrow F(A)$ , and defining  $F(f) = \alpha_B \circ f \circ \alpha_A^{-1}$  for a morphism  $f: A \rightarrow B$  in  $\mathcal{C}$ . Choose  $\alpha$  to be the identity morphisms if  $A \in \text{sk}(\mathcal{C})$ , then  $FJ = \text{id}_{\text{sk}(\mathcal{C})}$ ; the  $\alpha_A$  specify a natural isomorphism  $\alpha: \text{id} \rightarrow JF$ .

A category is connected if any two objects can be connected by a sequence of morphisms. Then a groupoid is connected iff any two of its objects are isomorphic. The group of endomorphisms of any object  $C$  is then a skeleton of  $\mathcal{C}$ , so we can generalize our results about skeletons to give the relationship between a fundamental group and a fundamental groupoid of a path connected space  $X$ .

**Proposition 3.1.** Let  $X$  be a path connected space. Then for each  $x \in X$ , the inclusion  $\pi_1(X, x) \rightarrow \Pi(X)$  is an equivalence of categories.

*Proof.* View  $\pi_1(X, x)$  as a groupoid with one object  $x$ : then  $\pi_1(X, x)$  is a skeleton of  $\Pi(X)$  and we are done.  $\square$

May's presentation and proofs are very concise and elegant. I like this.