nLab

Introduction to Topology -- 2

This page is a detailed introduction to basic topological homotopy theory. We introduce the fundamental group of topological spaces and the concept of covering spaces. Then we prove the fundamental theorem of covering spaces, saying that they are equivalent to permutation representations of the fundamental group. This is a simple topological version of the general principle of *Galois theory* and has many applications. As one example application, we use it to prove that the fundamental group of the circle is the integers.

> *Under construction.*

main page: *Introduction to Topology*

previous chapter: *Introduction to Topology 1 -- Point-set topology*

this chapter: **Introduction to Topology 2 – Basic Homotopy Theory**

For introduction to more general and abstract *homotopy theory* see instead at *Introduction to Homotopy Theory*.

Basic Homotopy Theory

1. Homotopy
   - Fundamental group
   - Groupoids
2. Covering spaces
   - Monodromy
   - Reconstruction
3. Topological Galois theory
   - Fundamental theorem of covering spaces
   - Applications
4. References

Context

Topology

Homotopy theory

In order to handle topological spaces, to compute their properties and distinguish them, it turns out to be useful to consider not just continuity within a topological space, but also continuous deformations of continuous functions *between*

topological spaces. This is the concept of *homotopy*, and its study is *homotopy theory*. We introduce the basic concept and consider its most fundamental application: the fundamental group and its relation to the classification of covering spaces.

1. Homotopy

It is clear that for $n \geq 1$ the Euclidean space $\mathbb{R}^n$ or equivalently the open ball $B_0^\circ(1)$ in $\mathbb{R}^n$ is *not* homeomorphic to the point space $* = \mathbb{R}^0$ (simply because there is not even a bijection between the underlying sets). Nevertheless, intuitively the n-ball is a "continuous deformation" of the point, obtained as the radius of the n-ball tends to zero.

This intuition is made precise by observing that there is a continuous function out of the product topological space (this example) of the open ball with the closed interval

$$\eta : [0,1] \times B_0^\circ(1) \longrightarrow B_0^\circ(1)$$

which is given by rescaling:

$$(t,x) \mapsto t \cdot x \;.$$

This continuously interpolates between the open ball and the point, in that for $t = 1$ it restricts to the identity, while for $t = 0$ it restricts to the map constant on the origin.

We may summarize this situation by saying that there is a diagram of continuous functions of the form

$$\begin{array}{ccc} B_0^\circ(1) \times \{0\} & \overset{\exists !}{\longrightarrow} & * \\ \downarrow && \downarrow^{\mathrm{const}_0} \\ [0,1] \times B_0^\circ(1) & \overset{(t,x) \mapsto t \cdot x}{\longrightarrow} & B_0^\circ(1) \\ \uparrow & \nearrow_{\simeq} & \\ B_0^\circ(1) \times \{1\} && \end{array}$$

Such "continuous deformations" are called *homotopies*:

In the following we use this terminlogy:

Definition 1.1. (topological interval)

The *topological interval* is

1. the closed interval $[0,1] \subset \mathbb{R}^1$ regarded as a topological space in the standard way, as a subspace of the real line with its Euclidean metric topology,

2. equipped with the continuous functions

1. $\mathrm{const}_0 : * \to [0,1]$

2. $\mathrm{const}_1 : * \to [0,1]$

which include the point space as the two endpoints, respectively

3. equipped with the (unique) continuous function

$$[0,1] \longrightarrow *$$

to the point space (which is the terminal object in Top)

regarded, in summary, as a factorization

$$\nabla_* : * \sqcup * \xrightarrow{(\mathrm{const}_0, \mathrm{const}_1)} [0,1] \longrightarrow *$$

of the codiagonal on the point space, namely the unique continuous function ∇_* out of the disjoint union space $* \sqcup * \simeq \mathrm{Disc}(\{0,1\})$ (homeomorphic to the discrete topological space on two elements).

Definition 1.2. (homotopy)

Let $X, Y \in$ Top be two topological spaces and let

$$f, g : X \longrightarrow Y$$

be two continuous functions between them.

A *(left) homotopy* from f to g, to be denoted

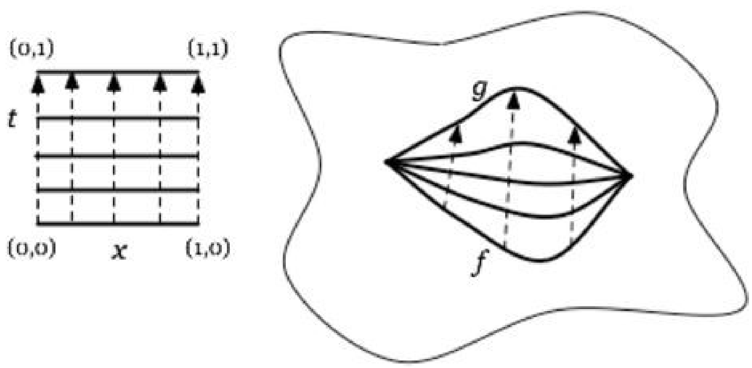
$$\eta : f \Rightarrow g \,,$$

is a continuous function

$$\eta : X \times [0,1] \longrightarrow Y$$

out of the product topological space (this example) of X the topological interval (def. 1.1) such that this makes the following diagram in Top commute:

$$\begin{tikzcd} 0 \times X \arrow[d, "(\mathrm{id}, \mathrm{const}_0)"'] \arrow[dr, "f"] & \\ X \times [0,1] \arrow[r, "\eta"] & Y \,. \\ \{1\} \times X \arrow[u, "(\mathrm{id}, \mathrm{const}_1)"] \arrow[ur, "g"'] & \end{tikzcd}$$



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hence such that

$$\eta(-,0) = f \qquad \text{and} \qquad \eta(-,1) = g \,.$$

If there is a homotopy $f \Rightarrow g$ (possibly unspecified) we say that f is *homotopic* to g, denoted

$$f \sim_h g \,.$$

Proposition 1.3. ***(homotopy is an equivalence relation)***

Let $X, Y \in$ Top be two topological spaces. Write $\mathrm{Hom}_{\mathrm{Top}}(X,Y)$ for the set of continuous functions from X to Y.

Then the relating of being homotopic (def. 1.2) is an equivalence relation on this set. The correspnding quotient set

$$[X,Y] \coloneqq \mathrm{Hom}_{\mathrm{Top}}(X,Y)/\sim_h$$

is called the set of homotopy classes of continuous functions.

Moreover, this equivalence relation is compatible with composition of continuous functions:

For $X, Y, Z \in$ Top three topological spaces, there is a unique function

$$[X,Y] \times [Y,Z] \longrightarrow [X,Z]$$

such that the following diagram commutes:

$$\begin{array}{ccc} \mathrm{Hom}_{\mathrm{Top}}(X,Y) \times \mathrm{Hom}_{\mathrm{Top}}(Y,Z) & \overset{\circ_{X,Y,Z}}{\longrightarrow} & \mathrm{Hom}_{\mathrm{Top}}(X,Z) \\ \downarrow && \downarrow \\ [X,Y] \times [Y,Z] & \longrightarrow & [X,Z] \end{array} \,.$$

Proof. To see that the relation is reflexive: A homotopy $f \Rightarrow f$ from a function f to itself is given by the function which is constant on the topological interval:

$$X \times [0,1] \overset{\mathrm{pr}_1}{\longrightarrow} X \,.$$

This is continuous becaue projections out of product topological spaces are continuous, by the universal property of the Cartesian product.

To see that the relation is symmetric: If $\eta : f \Rightarrow g$ is a homotopy then

$$\begin{array}{ccccc} X \times [0,1] & \overset{\mathrm{id}_X \times (1-(-))}{\longrightarrow} & X \times [0,1] & \overset{\eta}{\longrightarrow} & X \\ (x,t) & \mapsto & (x, 1-t) & \mapsto & \eta(x, 1-t) \end{array}$$

is a homotopy $g \Rightarrow f$. This is continuous because $1-(-)$ is a polynomial function, and polynomials are continuous, and because Cartesian product and composition of continuous functions is again continuous.

Finally to see that the relation is transitive: If $\eta_1 : f \Rightarrow g$ and $\eta_2 : g \Rightarrow h$ are two composable homotopies, then consider the "X-parameterized path concatenation"

$$
\begin{array}{ccc}
X \times [0,1] & \overset{\eta_2 \circ \eta_1}{\longrightarrow} & X \\
(x,t) & \mapsto & \left\{ \begin{array}{ccc} \eta_1(x, 2t) & | & t \leq 1/2 \\ \eta_2(x, 2t-1) & | & t \leq 1/2 \end{array} \right.
\end{array}
$$

To see that this is continuous, observe that $\{X \times [0,1/2] \subset X, X \times [1/2,1] \subset X\}$ is a cover of $X \times [0,1]$ by closed subsets (in the product topology) and because $\eta_1(-, 2(-))$ and $\eta_2(-, 2(-)-1)$ are continuous (being composites of Cartesian products of continuous functions) and agree on the intersection $X \times \{1/2\}$. Hence the continuity follows by this example.

Finally to see that homotopy respects composition: Let

$$
X \overset{f_1}{\longrightarrow} Y \underoverset{\underset{f'_2}{\longrightarrow}}{\overset{f_2}{\longrightarrow}}{} Z \overset{f_3}{\longrightarrow} W
$$

be continuous functions, and let

$$
\eta : f_2 \Rightarrow f'_2
$$

be a homotopy. It is sufficient to show that then there is a homotopy of the form

$$
f_3 \circ f_2 \circ f_1 \Rightarrow f_3 \circ f'_2 \circ f_1 \;.
$$

This is exhibited by the following diagram

$$
\begin{array}{ccccccc}
X & \overset{f_1}{\longrightarrow} & Y & & & & \\
{}^{(\mathrm{id}_X, \mathrm{const}_0)}\downarrow & & {}^{(\mathrm{id}_Y, \mathrm{const}_0)}\downarrow & \searrow^{f_2} & & & \\
X \times [0,1] & \overset{f_1 \times \mathrm{id}_{[0,1]}}{\longrightarrow} & Y \times [0,1] & \overset{\eta}{\longrightarrow} & Z & \overset{f_3}{\longrightarrow} & W \;. \\
{}^{(\mathrm{id}_X, \mathrm{const}_1)}\uparrow & & {}^{(\mathrm{id}, \mathrm{const}_1)}\uparrow & \nearrow_{f'_2} & & & \\
X & \underset{f_1}{\longrightarrow} & Y & & & &
\end{array}
$$

▮

Remark 1.4. (**homotopy category**)

Prop. 1.3 means that homotopy classes of continuous functions are the morphisms in a category whose objects are still the topological spaces.

This category (at least when restricted to spaces that admit the structure of CW-complexes) is called the *classical homotopy category*, often denoted

$$
\mathrm{Ho}(\mathrm{Top}) \;.
$$

Hence for X, Y topological spaces, then

$$
\mathrm{Hom}_{\mathrm{Ho}(\mathrm{Top})}(X,Y) = [X,Y]
$$

Moreover, sending a continuous function to its homotopy class is a functor

$$\kappa : \mathrm{Top} \longrightarrow \mathrm{Ho}(\mathrm{Top})$$

from the ordinary category Top of topological spaces with actual continuous functions between them.

Definition 1.5. **(homotopy equivalence)**

Let $X, Y \in$ Top be two topological spaces.

A continuous function

$$f : X \longrightarrow Y$$

is called a *homotopy equivalence* if there exists

1. a continuous function the other way around,

$$g : Y \longrightarrow X$$

2. homotopies (def. 1.2) from the two composites to the respective identity function:

$$f \circ g \Rightarrow \mathrm{id}_Y$$

and

$$g \circ f \Rightarrow \mathrm{id}_X \,.$$

We indicate that a continuous function is a homotopy equivalence by writing

$$X \overset{\simeq_h}{\longrightarrow} Y \,.$$

If there exists *some* (possibly unspecified) homotopy equivalence between topological spaces X and Y we write

$$X \simeq_h Y \,.$$

Remark 1.6. **(homotopy equivalences are the isomorphisms in the homotopy category)**

In view of remark 1.4 a continuous function f is a homotopy equivalence precisely if its image $\kappa(f)$ in the homotopy category is an isomorphism.

Example 1.7. **(homeomorphism is homotopy equivalence)**

Every homeomorphism is a homotopy equivalence (def. 1.5).

Proposition 1.8. ***(homotopy equivalence is equivalence relation)***

Being homotopy equivalent is an equivalence relation on the class of topological spaces.

Proof. This is immediate from remark 1.6 by general properties of categories and

functors.

But for the record we spell it out. This involves the construction already used in the proof of prop. 1.3:

It is clear that the relation it reflexive and symmetric. To see that it is transitive consider continuous functions

$$X \underoverset{\longleftarrow}{\overset{f_1}{\longrightarrow}}{g_1} Y \underoverset{\longleftarrow}{\overset{f_2}{\longrightarrow}}{g_2} Z$$

and homotopies

$$\begin{aligned} g_1 \circ f_1 \Rightarrow \mathrm{id}_X && f_1 \circ g_1 \Rightarrow \mathrm{id}_Y \\ g_2 \circ f_2 \Rightarrow \mathrm{id}_Y && f_2 \circ g_2 \Rightarrow \mathrm{id}_Z \,. \end{aligned}$$

We need to produce homotopies of the form

$$(g_1 \circ g_2) \circ (f_2 \circ f_1) \Rightarrow \mathrm{id}_X$$

and

$$(f_2 \circ f_1) \circ (g_1 \circ g_2) \Rightarrow \mathrm{id}_Y \,.$$

Now the diagram

$$\begin{array}{ccccccc} X & \overset{f_1}{\longrightarrow} & Y \\ {}^{\mathllap{(\mathrm{id}_X, \mathrm{const}_0)}}\downarrow && {}^{\mathllap{(\mathrm{id}_Y, \mathrm{const}_0)}}\downarrow & \searrow^{\mathrlap{g_2 \circ f_2}} \\ X \times [0,1] & \overset{f_1 \times \mathrm{id}_{[0,1]}}{\longrightarrow} & Y \times [0,1] & \overset{\eta}{\longrightarrow} & Y & \overset{g_1}{\longrightarrow} & X \,, \\ {}^{\mathllap{(\mathrm{id}_X, \mathrm{const}_1)}}\uparrow && {}^{\mathllap{(\mathrm{id}, \mathrm{const}_1)}}\uparrow & \nearrow_{\mathrlap{\mathrm{id}_Y}} \\ X & \underset{f_1}{\longrightarrow} & Y \end{array}$$

with η one of the given homotopies, exhibits a homotopy $(g_1 \circ g_2) \circ (f_2 \circ f_1) \Rightarrow g_1 \circ f_1$. Composing this with the given homotopy $g_1 \circ f_1 \Rightarrow \mathrm{id}_X$ gives the first of the two homotopies required above. The second one follows by the same construction, just with the lables of the functions exchanged. ▮

Definition 1.9. **(contractible topological space)**

A topological space X is called *contractible* if the unique continuous function to the point space

$$X \overset{\simeq_h}{\longrightarrow} *$$

is a homotopy equivalence (def. 1.5).

Remark 1.10. **(contractible topological spaces are the terminal objects in the homotopy category)**

In view of remark 1.4, a topological space X is contractible (def. 1.9) precisely if its image $\kappa(X)$ in the classical homotopy category is a terminal object.

Example 1.11. (closed ball and Euclidean space are contractible)

Let $B^n \subset \mathbb{R}^n$ be the unit open ball or closed ball in Euclidean space. This is contractible (def. 1.9):

$$p : B^n \overset{\simeq_h}{\longrightarrow} * \,.$$

The homotopy inverse function is necessarily constant on a point, we may just as well choose it to go pick the origin:

$$\mathrm{const}_0 \;:\; * \longrightarrow B^n \,.$$

For one way of composing these functions we have the equality

$$p \circ \mathrm{const}_0 = \mathrm{id}_*$$

with the identity function. This is a homotopy by prop. 1.3.

The other composite is

$$\mathrm{const}_0 \circ p = \mathrm{const}_0 \;:\; B^n \longrightarrow B^n \,.$$

Hence we need to produce a homotopy

$$\mathrm{const}_0 \Rightarrow \mathrm{id}_{B^n}$$

This is given by the function

$$\begin{array}{ccc} B^n \times [0,1] & \overset{\eta}{\longrightarrow} & B^n \\ (x,t) & \mapsto & t x \end{array} \,,$$

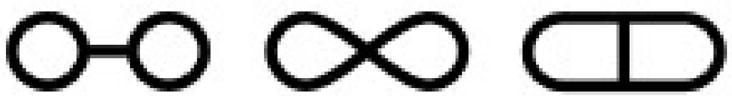
where on the right we use the multiplication with respect to the standard real vector space structure in $\mathbb{R}^n$.

Since the open ball is homeomorphic to the whole Cartesian space $\mathbb{R}^n$ (this example) it follows with example 1.7 and example 1.3 that also $\mathbb{R}^n$ is a contractible topological space:

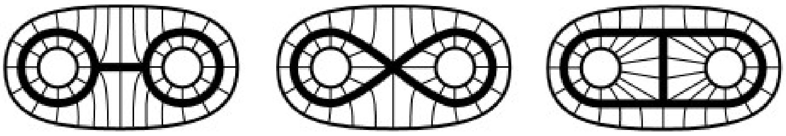
$$\mathbb{R}^n \overset{\simeq_h}{\longrightarrow} * \,.$$

In direct generalization of the construction in example 1.11 one finds further examples as follows:

Example 1.12. The following three graphs



(i.e. the evident topological subspaces of the plane $\mathbb{R}^2$ that these pictures indicate) are not homeomorphic. But they are homotopy equivalent, in fact they are each homotopy equivalent to the disk with two points removed, by the homotopies indicated by the following pictures:



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Fundamental group

Definition 1.13. (homotopy relative boundary)

Let X be a topological space and let

$$\gamma_1, \gamma_2 \;:\; [0,1] \longrightarrow X$$

be two paths in X, i.e. two continuous functions from the closed interval to X, such that their endpoints agree:

$$\gamma_1(0) = \gamma_2(0) \qquad \gamma_1(1) = \gamma_2(1)\,.$$

Then a homotopy relative boundary from γ_1 to γ_2 is a homotopy (def. 1.2)

$$\eta \;:\; \gamma_1 \Rightarrow \gamma_2$$

such that it does not move the endpoints:

$$\eta(0,-) = \mathrm{const}_{\gamma_1(0)} = \mathrm{const}_{\gamma_2(0)} \qquad \eta(1,-) = \mathrm{const}_{\gamma_1(0)} = \mathrm{const}_{\gamma_2(1)}\,.$$

Proposition 1.14. ***(homotopy relative boundary is equivalence relation on sets of paths)***

Let X be a topological space and let $x, y \in X$ be two points. Write

$$P_{x,y}X$$

for the set of paths γ in X with $\gamma(0) = x$ and $\gamma(1) = y$.

Then homotopy relative boundary (def. 1.13) is an equivalence relation on $P_{x,y}X$.

The corresponding set of equivalence classes is denoted

$$\mathrm{Hom}_{\Pi_1(X)}(x,y) \;\coloneqq\; (P_{x,y}X)/\sim\,.$$

Recall the operations on paths: path concatenation $\gamma_2 \cdot \gamma_1$, path reversion $\overline{\gamma}$ and constant paths

Proposition 1.15. ***(concatenation of homotopy relative boundary-classes of paths)***

For X a topological space, then the operation of path concatenation descends to homotopy relative boundary equivalence classes, so that for all $x, y, z \in X$ there is a function

$$\begin{array}{ccc} \mathrm{Hom}_{\Pi_1(X)}(x,y) \times \mathrm{Hom}_{\Pi_1(X)}(y,z) & \longrightarrow & \mathrm{Hom}_{\Pi_1(X)}(x,z) \\ ([\gamma_1],[\gamma_2]) & \mapsto & [\gamma_2]\cdot[\gamma_1] \coloneqq [\gamma_2 \cdot \gamma_1] \end{array} .$$

Moreover,

1. *this composition operation is associative in that for all $x, y, z, w \in X$ and $[\gamma_1] \in \mathrm{Hom}_{\Pi_1(X)}(x,y)$, $[\gamma_2] \in \mathrm{Hom}_{\Pi_1(X)}(y,z)$ and $[\gamma_3] \in \mathrm{Hom}_{\Pi_1(X)})(z,w)$ then*

$$[\gamma_3]\cdot([\gamma_2]\cdot[\gamma_1]) \;=\; ([\gamma_3]\cdot[\gamma_2])\cdot[\gamma_1]$$

2. *this composition operation is unital with neutral elements the constant paths in that for all $x, y \in X$ and $[\gamma] \in \mathrm{Hom}_{\Pi_1(X)}(x,y)$ we have*

$$[\mathrm{const}_y]\cdot[\gamma] = [\gamma] = [\gamma]\cdot[\mathrm{const}_x] \,.$$

3. *this composition operation has inverse elements given by path reversal in that for all $x, y \in X$ and $[\gamma] \in \mathrm{Hom}_{\Pi_1(X)}(x,y)$ we have*

$$[\overline{\gamma}]\cdot[\gamma] = [\mathrm{const}_x] \qquad [\gamma]\cdot[\overline{\gamma}] = [\mathrm{const}_y] \,.$$

Definition 1.16. **(fundamental groupoid and fundamental groups)**

Let X be a topological space. Then set of points of X together with the sets $\mathrm{Hom}_{\Pi_1(X)}(x,y)$ of homotopy relative boundary-classes of paths (def. 1.13) for all points of points and equipped with the concatenation operation from prop. 1.15 is called the *fundamental groupoid* of X, denoted

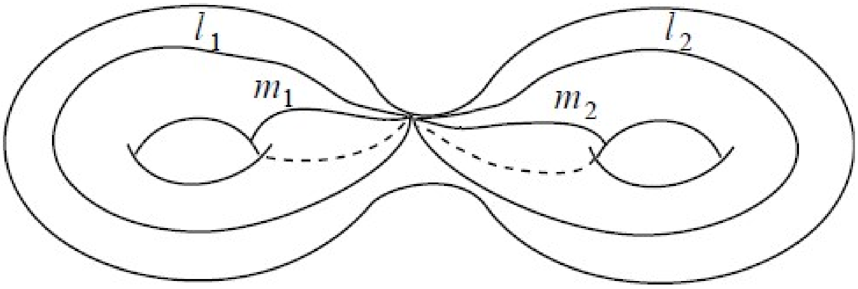
$$\Pi_1(X) \,.$$

Given a choice of point $x \in X$, then one writes

$$\pi_1(X,x) \;\coloneqq\; \mathrm{Hom}_{\Pi_1(X)}(x,x) \,.$$

Prop. 1.15 says that under concatenation of paths, this set is a group. As such it is called the *fundamental group* of X at x.

The following picture indicates the four non-equivalent non-trivial generators of the fundamental group of the oriented surface of genus 2:



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Example 1.17. (**fundamental group of Euclidean space**)

For $n \in \mathbb{N}$ and $x \in \mathbb{R}^n$ any point in the n-dimensional Euclidean space (regarded with its metric topology) we have that the fundamental group (def. 1.16) at that point is trivial:

$$\pi_1(\mathbb{R}^n, x) = * \;.$$

Remark 1.18. **(basepoints)**

Definition 1.16 intentionally offers two variants of the defintion.

The first, the *fundamental groupoid* is canonically given, without choosing a basepoint. As a result, it is a structure that is not quite a group but, slightly more generally, a "groupoid" (a "group with many objects"). We discuss the concept of groupoids below.

The second, the fundamental group, is a genuine group, but its definition requires picking a base point $x \in X$.

In this context it is useful to say that

1. a *pointed topological space* (X, x) is

   1. a topological space X;

   2. a $x \in X$ in the underlying set.

2. a homomorphism of pointed topological spaces $f : (X, x) \longrightarrow (Y, y)$ is a base-point preserving continuous function, namely

   1. a continuous function $f : X \longrightarrow Y$

   2. such that $f(x) = y$.

Hence there is a category, to be denoted, $\mathrm{Top}^{*/}$, whose objects are the pointed topological spaces, and whose morphisms are tbe base-point preserving continuous functions.

Similarly, a homotopy between morphisms $f, f' : (X, x) \to (Y, y)$ in $\mathrm{Top}^{*/}$ is a homotopy $\eta : f \Rightarrow f'$ of underlying continuous functions, as in def. 1.2, such that

the corresponding function

$$\eta : X \times [0,1] \longrightarrow Y$$

preserves the basepoints in that

$$\underset{t \in [0,1]}{\forall} \eta(x,t) = y \; .$$

These pointed homotopies still form an equivalence relation as in prop. 1.3 and hence quotienting these out yields the pointed analogue of the homotopy category from def. 1.4, now denoted

$$\kappa : \mathrm{Top}^{*/} \longrightarrow \mathrm{Ho}(\mathrm{Top}^{*/}) \; .$$

In general it is hard to explicitly compute the fundamental group of a topological space. But often it is already useful to know if two spaces have the same fundamental group or not:

Definition 1.19. **(pushforward of elements of fundamental groups)**

Let (X,x) and (Y,y) be pointed topological space (remark 1.18) and let

$$f : X \longrightarrow Y$$

be a continuous function which respects the chosen points, in that $f(x) = y$.

Then there is an induced homomorphism of fundamental groups (def. 1.16)

$$\begin{array}{ccc} \pi_1(X,x) & \overset{f_*}{\longrightarrow} & \pi_1(Y,y) \\ [\gamma] & \mapsto & [f \circ \gamma] \end{array}$$

given by sending a closed path $\gamma : [0,1] \to X$ to the composite

$$f \circ \gamma : [0,1] \overset{\gamma}{\longrightarrow} X \overset{f}{\longrightarrow} Y \; .$$

Remark 1.20. **(fundamental group is functor on pointed topological spaces)**

The pushforward operation in def. 1.19 is functorial, now on the category $\mathrm{Top}^{*/}$ of pointed topological spaces (remark 1.18)

$$\pi_1 : \mathrm{Top}^{*/} \longrightarrow \mathrm{Grp} \; .$$

Proposition 1.21. ***(fundamental group depends only on homotopy classes)***

Let $X,Y \in \mathrm{Top}^{*/}$ be pointed topological space and let $f_1, f_2 : X \longrightarrow Y$ be two base-point preserving continuous functions. If there is a pointed homotopy (def. 1.2, remark 1.18)

$$\eta : f_1 \Rightarrow f_2$$

then the induced homomorphisms on fundamental groups (def. 1.19) agree

$$(f_1)_* = (f_2)_* : \pi_1(X,x) \to \pi_1(Y,y) \,.$$

In particular if $f :; X \longrightarrow Y$ is a homotopy equivalence (def. 1.5) then $f_* : \pi_1(X,x) \to \pi_1(Y,y)$ is an isomorphism.

Proof. This follows by the fact that homotopy respects composition (prop. 1.3):

If $\gamma : [0,1] \longrightarrow X$ is a closed path representing a given element of $\pi_1(X,x)$, then the homotopy $f_1 \Rightarrow f_2$ induces a homotopy

$$f_1 \circ \gamma \Rightarrow f_2 \circ \gamma$$

and therefore these represent the same elements in $\pi_1(Y,y)$.

If follows that if f is a homotopy equivalence with homotopy inverse g, then $g_* : \pi_1(Y,y) \to \pi_1(X,x)$ is an inverse morphism to $f_* : \pi_1(X,x) \to \pi_1(Y,y)$ and hence f_* is an isomorphism. ■

Remark 1.22. Prop. 1.21 says that the fundamental group functor from def. 1.19 and remark 1.20 factors through the classical pointed homotopy category from remark 1.18:

$$\begin{array}{ccc} \mathrm{Top}^{*/} & \overset{\pi_1}{\longrightarrow} & \mathrm{Grp} \\ {}^{\kappa}\downarrow & \nearrow \\ \mathrm{Ho}(\mathrm{Top}^{*/}) \end{array} \,.$$

Definition 1.23. **(simply connected topological space)**

A topological space X for which

1. $\pi_0(X) \simeq *$ (path connected)

2. $\pi_1(X,x) \simeq 1$ (the fundamental group is trivial, def. 1.16),

is called *simply connected*.

We will need also the following local version:

Definition 1.24. **(semi-locally simply connected topological space)**

A topological space X is called *semi-locally simply connected* if every point $x \in X$ has a neighbourhood $U_x \subset X$ such that every loop in X is contractible as a loop in X, hence such that the induced morphism of fundamental groups (def. 1.19)

$$\pi_1(U,x) \to \pi_1(X,x)$$

is trivial (i.e. sends everything to the neutral element).

If every x has a neighbourhood U_x which is itself simyply connected, then X is called a *locally simply connected topological space*. This implies semi-local simply-connectedness.

Example 1.25. (**Euclidean space is simply connected**)

For $n \in \mathbb{N}$, then the Euclidean space $\mathbb{R}^n$ is a simply connected topological space (def. 1.23).

Groupoids

(...)

2. Covering spaces

Definition 2.1. (**covering space**)

Let X be a topological space. A *covering space* of X is a continuous function

$$p : E \longrightarrow X$$

such that there exists an open cover $\underset{i}{\sqcup} U_i \to X$, such that restricted to each U_i then $E \to X$ is homeomorphic over U_i to the product topological space (this example) of U_i with the discrete topological space (this example) on a set F_i,

In summary this says that $p : E \to X$ is a covering space if there exists a pullback diagram in Top of the form

$$\begin{array}{ccc} \underset{i}{\sqcup} U_i \times \mathrm{Disc}(F_i) & \longrightarrow & E \\ \downarrow & (\mathrm{pb}) & \downarrow^{p} \\ \underset{i \in I}{\sqcup} U_i & \longrightarrow & X \end{array} .$$

For $x \in U_i \subset X$ a point, then the elements in $F_x = F_i$ are called the *leaves* of the covering at x.

Given two covering spaces $p_i : E_i \to X$, then a homomorphism between them is a continuous function $f : E_1 \to E_2$ between the total covering spaces, which respects the fibers in that the following diagram commutes

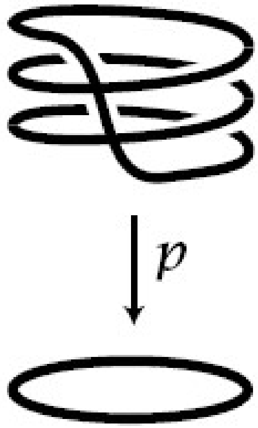
$$\begin{array}{ccccc} E_1 && \overset{f}{\longrightarrow} && E_2 \\ & \searrow && \swarrow & \\ && X && \end{array} .$$

This defines a category $\mathrm{Cov}(X)$ whose

- objects are the covering spaces over X;
- morphisms are the homomorphisms between these.

Example 2.2. (**covering of circle by circle**)

Regard the circle $S^1 = \{z \in \mathbb{C} \mid |z| = 1\}$ as the topological subspace of elements of



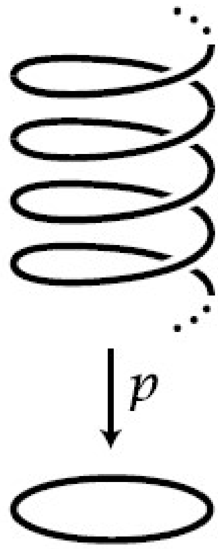
unit absolute value in the complex plane. For $k \in \mathbb{N}$, consider the continuous function

$$p \coloneqq (-)^k : S^1 \longrightarrow S^1$$

given by taking a complex number to its kth power. This may be thought of as the result of "winding the circle k times around itself". Precisely, for $k \geq 1$ this is a covering space (def. 2.1) with k leaves at each point.

graphics grabbed from Hatcher

Example 2.3. **(covering of circle by real line)**



Consider the continuous function

$$\exp(2\pi i(-)) : \mathbb{R}^1 \longrightarrow S^1$$

from the real line to the circle, which,

1. with the circle regarded as the unit circle in the complex plane $\mathbb{C}$, is given by

$$t \mapsto \exp(2\pi i t)$$

2. with the circle regarded as the unit circle in $\mathbb{R}^2$, is given by

$$t \mapsto (\cos(2\pi t), \sin(2\pi t)) \,.$$

We may think of this as the result of "winding the line around the circle ad infinitum". Precisely, this is a covering space (def. 2.1) with the leaves at each point forming the set $\mathbb{Z}$ of natural numbers.

Definition 2.4. **(action of fundamental group on fibers of covering)**

Let $E \overset{\pi}{\longrightarrow} X$ be a covering space (def. 2.1)

Then for $x \in X$ any point, and any choice of element $e \in F_x$ of the leaf space over x, there is, up to homotopy, a unique way to lift a representative path in X of an element γ of the the fundamental group $\pi_1(X,x)$ (def. 1.16) to a continuous path in E that starts at e. This path necessarily ends at some (other) point $\rho_\gamma(e) \in F_x$ in the same fiber. This construction provides a function

$$\begin{array}{ccccc} \rho & : & F_x \times \pi_1(X,x) & \longrightarrow & F_x \\ & & (e,\gamma) & \mapsto & \rho_\gamma(e) \end{array}$$

from the Cartesian product of the leaf space with the fundamental group. This function is compatible with the group-structure on $\pi_1(X,x)$, in that the following diagrams commute:

$$
\begin{tikzcd}
F_x \times \{\mathrm{const}_x\} \arrow[rr] \arrow[dr, "\mathrm{id}"'] & & F_x \times \pi_1(X,x) \arrow[dl, "\rho"] \\
& F_x &
\end{tikzcd}
\quad
\left(
\begin{array}{c}
\text{the neutral element,} \\
\text{i.e. the constant loop,} \\
\text{acts trivially}
\end{array}
\right)
$$

and

$$
\begin{tikzcd}
F_x \times \pi_1(X,x) \times \pi_1(X,x) \arrow[r, "\rho \times \mathrm{id}"] \arrow[d, "\mathrm{id} \times ((-)\cdot(-))"'] & F_x \times \pi_1(X,x) \arrow[d, "\rho"] \\
F_x \times \pi_1(X,x) \arrow[r, "\rho"'] & F_x
\end{tikzcd}
\quad
\left(
\begin{array}{c}
\text{acting with two group elements} \\
\text{is the same as} \\
\text{first multiplying them} \\
\text{and then acting with their product element}
\end{array}
\right)
.
$$

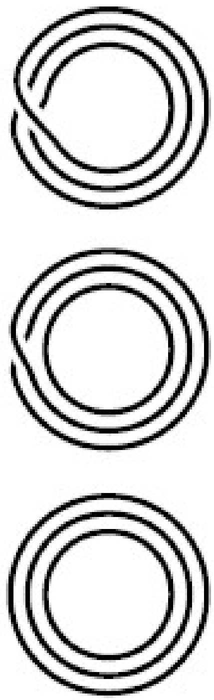
One says that ρ is an *action* or *permutation representation* of $\pi_1(X,x)$ on F_x.

For G any group, then there is a category $G\,\mathrm{Set}$ whose objects are sets equipped with an action of G, and whose morphisms are functions which respect these actions. The above construction is a functor of the form

$$
\mathrm{Fib}_x \;:\; \mathrm{Cov}(X) \longrightarrow \pi_1(X,x)\mathrm{Set}\,.
$$

Example 2.5. **(three-sheeted covers of the circle)**

There are, up to isomorphism, three different 3-sheeted covering spaces of the circle S^1.



The one from example 2.2 for $k = 3$. Another one. And the trivial one. Their corresponding permutation actions may be seen from the pictures on the right.

graphics grabbed from Hatcher

Proposition 2.6. ***(covering projections are open maps)***

If $p : E \to X$ is a covering space projection, then p is an open map.

Proof. By definition of covering space there exists an open cover $\{U_i \subset X\}_{i \in I}$ and homeomorphisms $p^{-1}(U_i) \simeq U_i \times \mathrm{Disc}(F_i)$ for all $i \in I$. Since the projections out of a product topological space are open maps (this prop.), it follows that p is an open map when restricted to any of the $p^{-1}(U_i)$. But a general open subset $W \subset E$ is the union of its restrictions to these subspaces:

$$
W = \underset{i \in I}{\cup} \left(W \cap p^{-1}(U_i)\right)\,.
$$

Since images preserve unions (this prop.) it follows that

$$
p(W) = \underset{i \in I}{\cup} p\left(W \cap p^{-1}(U_i)\right)
$$

is a union of open sets, and hence itself open. ▮

We discuss left lifting properties satisfied by covering spaces.

1. path-lifting property,
2. homotopy-lifting propery,
3. the lifting theorem.

Lemma 2.7. ***(path lifting property)***

Let $p : E \to X$ be any covering space. Given

1. *$\gamma : [0,1] \to X$ a path in X,*
2. *$\hat{x}_0 \in E$ be a lift of its starting point, hence such that $p(\hat{x}_0) = \gamma(0)$*

then there exists a unique path $\hat{\gamma} : [0,1] \to E$ such that

1. *it is a lift of the original path: $p \circ \hat{\gamma} = \gamma$;*
2. *it starts at the given lifted point: $\hat{\gamma}(0) = \hat{x}_0$.*

In other words, every commuting diagram in Top of the form

$$\begin{array}{ccc} \{0\} & \overset{\hat{x}_0}{\longrightarrow} & E \\ \downarrow && \downarrow^{p} \\ [0,1] & \underset{\gamma}{\longrightarrow} & X \end{array}$$

has a unique lift:

$$\begin{array}{ccc} \{0\} & \overset{\hat{x}_0}{\longrightarrow} & E \\ \downarrow & {}^{\hat{\gamma}}\nearrow & \downarrow^{p} \\ [0,1] & \underset{\gamma}{\longrightarrow} & X \end{array} .$$

####### Proof

First consider the case that the covering space is trival, hence of the Cartesian product form

$$\mathrm{pr}_1 \;\colon\; X \times \mathrm{Disc}(S) \longrightarrow X \,.$$

By the universal property of the product topological spaces in this case a lift $\hat{\gamma} : [0,1] \to X \times \mathrm{Disc}(S)$ is equivalently a pair of continuous functions

$$\mathrm{pr}_1(\hat{\gamma}) : [0,1] \to X \qquad \mathrm{pr}_2(\hat{\gamma}) : [0,1] \to \mathrm{Disc}(S) \,,$$

Now the lifting condition explicitly fixes $\mathrm{pr}_1(\hat{\gamma}) = \gamma$. nMoreover, a continuous function into a discrete topological space $\mathrm{Disc}(S)$ is locally constant, and since $[0,1]$ is a connected topological space this means that $\mathrm{pr}_2(\hat{\gamma})$ is in fact a constant

function (this example), hence uniquely fixed to be $\mathrm{pr}_2(\hat{\gamma}) = \hat{x}_0$.

This shows the statement for the case of trivial covering spaces.

Now consider any covering space $p : E \to X$. By definition of covering spaces, there exists for every point $x \in X$ a open neighbourhood $U_x \subset X$ such that the restriction of E to U_x becomes a trivial covering space:

$$p^{-1}(U_x) \simeq U_x \times \mathrm{Disc}(p^{-1}(x)) \;.$$

Consider such a choice

$$\{U_x \subset X\}_{x \in X} \;.$$

This is an open cover of X. Accordingly, the pre-images

$$\{\gamma^{-1}(U_x) \subset [0,1]\}_{x \in X}$$

constitute an open cover of the topological interval $[0,1]$.

Now $[0,1]$ is a compact metric space and therefore the Lebesgue number lemma implies that there is a positive number $\epsilon \in (0,\infty)$ and cover of $[0,1]$ by open intervals of the form $(-\epsilon + x, x + \epsilon) \cap [0,1] \subset [0,1]$ which refines this cover. Again since $[0,1]$ is a compact topological space there is a finite set of such intervals which covers $[0,1]$. This means that we find a finite number of points

$$t_0 < t_1 < \cdots <_{n+1} \;\in [0,1]$$

with $t_0 = 0$ and $t_{n+1} = 1$ such that for all $0 < j \mathrm{leg} n$ there is $x_j \in X$ such that the corresponding path segment

$$\gamma([t_j, t_{j+1}]) \subset X$$

is contained in U_{x_j} from above.

Now assume that $\hat{\gamma}\vert_{[0,t_j]}$ has been found. Then by the triviality of the covering space over U_{x_j} and the first argument above, there is a unique lift of $\gamma\vert_{[t_j,t_{j+1}]}$ to a continuous function $\hat{\gamma}\vert_{[t_j,t_{j+1}]}$ with starting point $\hat{\gamma}(t_j)$. Since $[0,t_{j+1}]$ is the pushout $[0,t_j] \underset{\{t_j\}}{\sqcup} [t_j,t_{j+1}]$ (this example), it follows that $\hat{\gamma}\vert_{[0,t_j]}$ and $\hat{\gamma}\vert_{[t_j,t_{j+1}]}$ uniquely glue to a continuous function $\hat{\gamma}\vert_{[0,t_{j+1}]}$ which lifts $\gamma\vert_{[0,t_{j+1}]}$.

By induction over j, this yields the required lift $\hat{\gamma}$.

Conversely, given any lift, $\hat{\gamma}$, then its restrictions $\hat{\gamma}\vert_{[t_j,t_{j+1}]}$ are uniquely fixed by the above inductive argument. Therefore also the total lift is unique. ■

Proposition 2.8. ***(homotopy lifting property of covering spaces)***

Let $p : E \to X$ be a covering space. Then given a homotopy relative the starting

point between two paths in X, there is for every lift of these two paths to paths in E with the same starting point a unique homotopy between the lifted paths that lifts the given homotopy:

For commuting squares of the form

$$\begin{array}{ccc} \{0\} \times \{0,1\} & \longrightarrow & * \\ \downarrow & & \downarrow \\ [0,1] \times \{0,1\} & \longrightarrow & E \\ \downarrow & {}^{\hat \eta}\nearrow & \downarrow^{p} \\ [0,1] \times [0,1] & \underset{\eta}{\longrightarrow} & X \end{array}$$

there is a unique diagonal lift in the lower diagram, as shown.

Moreover if the homotopy η also fixes the endpoint, then so does the lifted homotopy $\hat \eta$.

Proof. The proof is analogous to that of lemma 2.7: The Lebesgue number lemma gives a partition of $[0,1] \times [0,1]$ into a finite number of squares such that the image of each under γ lands in an open subset over which the covering space trivializes. Then there is inductively a unique appropriate lift over each of these squares.

Finally, if the homotopy in X is constant also at the endpoint, hence on $\{1\} \times [0,1]$, then the function constant on $\hat \eta(1,1)$ is clearly a lift of the path $\mathrm{eta}\vert_{\{1\} \times [0,1]}$ and by uniqueness of the path lifting (lemma 2.7) this means that also $\hat \eta$ is constant on $\{1\} \times [0,1]$. ▮

Example 2.9. Let $(E,e) \overset{p}{\longrightarrow} (X,x)$ be a pointed covering space and let $f \colon (Y,y) \longrightarrow (X,x)$ be a point-preserving continuous function such that the image of the fundamental group of (Y,y) is contained within the image of the fundamental group of (E,e) in that of (X,x):

$$f_\ast(\pi_1(Y,y)) \subset p_\ast(\pi_1(E,e)) \quad \subset \pi_1(X,x) \,.$$

Then for ℓ_Y a path in (Y,y) that happens to be a loop, every lift of its image path $f \circ \ell$ in (X,x) to a path $\widehat{f \circ \ell_Y}$ in (E,e) is also a loop there.

Proof. By assumption, there is a loop ℓ_E in (E,e) and a homotopy fixing the endpoints of the form

$$\eta_X \;\colon\; p \circ \ell_E \Rightarrow f \circ \ell_Y \,.$$

Then by the homotopy lifting property (lemma 2.8), there is a homotopy in (E,e) fixing the starting point, of the form

$$\eta_E \;\colon\; \ell_E \Rightarrow \widehat{f \circ \ell_Y}$$

and lifting the homotopy η_X. Since η_X in addition fixes the endpoint, the uniqueness of the path lifting (lemma 2.7) implies that also η_E fixes the endpoint. Therefore η_E is in fact a homotopy between loops, and so weidehat $f \circ \ell_Y$ is indeed a loop. ▮

Proposition 2.10. ***(lifting theorem)***

Let

1. $p : E \to X$ *be a covering space;*
2. $e \in E$ *a point, with* $x \coloneqq p(e)$ *denoting its image,*
3. Y *be a connected and locally path-connected topological space;*
4. $y \in Y$ *a point*
5. $f : (Y, y) \longrightarrow (X, x)$ *a continuous function such that* $f(y) = x$.

Then the following are equivalent:

1. *There exists a lift* $\hat f$ *in the diagram*

$$\begin{array}{ccc} && (E, e) \\ & {}^{\mathllap{\hat f}}\nearrow & \downarrow^{\mathrlap{p}} \\ (Y, y) & \underset{f}{\longrightarrow} & (X, x) \end{array}$$

   of pointed topological spaces.

2. *The image of the fundamental group of* Y *under* f *in that of* X *is contained in the image of the fundamental group of* E *under* p*:*

$$f_*(\pi_1(Y, y)) \subset p_*(\pi_1(E, e))$$

Moreover, if Y *is path-connected, then the lift in the first item is unique.*

Proof. The implication $1) \Rightarrow 2)$ is immediate. We need to show that the second statement already implies the first.

Since Y is connected and locally path-connected, it is also a path-connected topological space (this prop.). Hence for every point $y' \in Y$ there exists a path γ connecting y with y' and hence a path $f \circ \gamma$ connecting x with $f(y')$. By the path-lifting property (lemma 2.7) this has a unique lift

$$\begin{array}{ccc} \{0\} & \overset{e}{\longrightarrow} & E \\ \downarrow & {}^{\widehat{f \circ \gamma}}\nearrow & \downarrow^{\mathrlap{p}} \\ [0,1] & \underset{f \circ \gamma}{\longrightarrow} & X \end{array}.$$

Therefore

$$\hat{f}(y') \coloneqq \widehat{f \circ \gamma}$$

if a lift of $f(y')$.

We claim now that this pointwise construction is independent of the choice γ, and that as a function of y' it is indeed continuous. This will prove the claim.

Now by the path lifting lemma 2.7 the lift $\widehat{\mathrm{f} \circ \gamma}$ is unique given $f \circ \gamma$, and hence $\hat{f}(y')$ depends at most on the choice of γ.

Hence let $\gamma' : [0,1] \to Y$ be another path in Y that connects y with y'. We need to show that then $\widehat{f \circ \gamma'} = \widehat{f \circ \gamma}$.

First observe that if γ' is related to γ by a homotopy, so that then also $f \circ \gamma'$ is related to $f \circ \gamma$ by a homotopy, then this is the statement of the homotopy lifting property of lemma 2.8.

Next write $\bar{\gamma}' \cdot \gamma$ for the path concatenation of the path γ with the reverse path of the path γ', hence a loop in Y, so that $f \circ (\bar{\gamma}' \cdot \gamma)$ is a loop in X. The assumption that $f_*(\pi_1(Y, y)) \subset p_*(\pi_1(E, e))$ implies (example 2.9) that the path $\widehat{f \circ (\bar{\gamma}' \cdot \gamma)}$ which lifts this loop to E is itself a loop in E.

By uniqueness of path lifting, this means that the lift of $f \circ (\gamma' \cdot (\bar{\gamma}' \cdot \gamma))$ coincides with that of $f \circ \gamma'$. But $\bar{\gamma}' \cdot (\gamma' \cdot \gamma)$ is homotopic (via reparameterization) to just γ. Hence it follows now with the first statement that the lift of $f \circ \gamma'$ indeed coincides with that of $f \circ \gamma$.

This shows that the above prescription for $\hat{f}$ is well defined.

It only remains to show that the function $\hat{f}$ obtained this way is continuous.

Let $y' \in Y$ be a point and $W_{\hat{f}(y')} \subset E$ an open neighbourhood of its image in E. It is sufficient to see that there is an open neighbourhood $V_{y'} \subset Y$ such that $\hat{f}(V_y) \subset W_{\hat{f}(y')}$.

Let $U_{f(y')} \subset X$ be an open neighbourhood over which p trivializes. Then the restriction

$$p^{-1}(U_{f(y')}) \cap W_{\hat{f}(y')} \;\subset\; U_{f(y')} \times \mathrm{Disc}(p^{-1}(f(y')))$$

is an open subset of the product space. Consider its further restriction

$$\left(U_{f(y')} \times \{\hat{f}(y')\}\right) \cap \left(p^{-1}(U_{f(y')}) \cap W_{\hat{f}(y')}\right)$$

to the leaf

$$U_{f(y')} \times \{\hat{f}(y')\} \;\subset\; U_{f(y')} \times p^{-1}(f(y'))$$

which is itself an open subset. Since p is an open map (this prop.), the subset

$$p\Big(\big(U_{f(y')} \times \{\hat{f}(y')\}\big) \cap \big(p^{-1}(U_{f(y')}) \cap W_{\hat{f}(y')}\big)\Big) \subset X$$

is open, hence so is its pre-image

$$f^{-1}\Big(p\Big(\big(U_{f(y')} \times \{\hat{f}(y')\}\big) \cap \big(p^{-1}(U_{f(y')}) \cap W_{\hat{f}(y')}\big)\Big)\Big) \;\subset\; Y\,.$$

Since Y is assumed to be locally path-connected, there exists a path-connected open neighbourhood

$$V_{y'} \subset f^{-1}\Big(p\Big(\big(U_{f(y')} \times \{\hat{f}(y')\}\big) \cap \big(p^{-1}(U_{f(y')}) \cap W_{\hat{f}(y')}\big)\Big)\Big)\,.$$

By the uniqueness of pah lifting, the image of that under $\hat{f}$ is

$$\begin{aligned} \hat{f}(V_{y'}) &= f(V_{y'}) \times \{\hat{f}(y')\} \\ &\subset p\Big(\big(U_{f(y')} \times \{\hat{f}(y')\}\big) \cap \big(p^{-1}(U_{f(y')}) \cap W_{\hat{f}(y')}\big)\Big) \times \{\hat{f}(y')\} \\ &\simeq \big(U_{f(y')} \times \{\hat{f}(y')\}\big) \cap \big(p^{-1}(U_{f(y')}) \cap W_{\hat{f}(y')}\big) \\ &\subset W_{\hat{f}(y')} \end{aligned}\,.$$

It remains to show that this lift is unique if Y is path-connected. (…) ▮

Monodromy

Definition 2.11. (monodromy of a covering space)

Let X be a topological space and $E \overset{p}{\to} X$ a covering space. Write $\Pi_1(X)$ for the fundamental groupoid of X.

Define a functor

$$\mathrm{Fib}_E \;:\; \Pi_1(X) \longrightarrow \mathrm{Set}$$

to the category Set of sets as follows:

1. to a point $x \in X$ assign the fiber $p^{-1}(\{x\}) \in \mathrm{Set}$;
2. to the homotopy class of a path γ connecting $x \coloneqq \gamma(0)$ with $y \coloneqq \gamma(1)$ in X assign the function $p^{-1}(\{x\}) \longrightarrow p^{-1}(\{y\})$ which takes $\hat{x} \in p^{-1}(\{x\})$ to the endpoint of a path $\hat{\gamma}$ in E which lifts γ through p with starting point $\hat{\gamma}(0) = \hat{x}$

$$\begin{aligned} p^{-1}(x) &\longrightarrow p^{-1}(y) \\ (\hat{x} = \hat{\gamma}(0)) &\mapsto \hat{\gamma}(1) \end{aligned}\,.$$

This construction is well defined for a given representative γ due to the unique path-lifting property of covering spaces (this lemma) and it is independent of the

choice of γ in the given homotopy class of paths due to the homotopy-lifting property (this lemma). Similarly, these two lifting properties give that this construction respects composition in $\Pi_1(X)$ and hence is indeed a functor.

Proposition 2.12. *Given a homomorphism between two covering spaces $E_i \overset{p_i}{\to} X$, hence a continuous function $f: E_1 \to E_2$ which respects fibers in that the diagram*

$$\begin{array}{ccc} E_1 && \overset{f}{\longrightarrow} && E_2 \\ & {}_{\mathllap{p_1}}\searrow && \swarrow_{\mathrlap{p_2}} \\ && X \end{array}$$

commutes, then the component functions

$$f|_{\{x\}} \;:\; p_1^{-1}(\{x\}) \longrightarrow p_2^{-1}(\{x\})$$

are compatible with the monodromy Fib_E (def. 2.11) along any path γ between points x and y from def. 2.11 in that the following diagrams of sets commute

$$\begin{array}{ccc} p_1^{-1}(x) & \overset{f|_{\{x\}}}{\longrightarrow} & p_2^{-1}(x) \\ {}^{\mathllap{\mathrm{Fib}_{E_1}([\gamma])}}\downarrow && \downarrow^{\mathrlap{\mathrm{Fib}_{E_2}([\gamma])}} \\ p_1^{-1}(y) & \underset{f|_{\{y\}}}{\longrightarrow} & p_2^{-1}(\{y\}) \end{array}$$

This means that f induces a natural transformation between the monodromy functors of E_1 and E_2, respectively, and hence that constructing monodromy is itself a functor from the category of covering spaces of X to that of permutation representations of the fundamental groupoid of X:

$$\mathrm{Fib} \;:\; \mathrm{Cov}(X) \longrightarrow \mathrm{Set}^{\Pi_1(X)} \,.$$

Example 2.13. **(fundamental groupoid of covering space)**

Let $E \overset{p}{\longrightarrow} X$ be a covering space.

Then the fundamental groupoid $\Pi_1(E)$ of the total space E is equivalently the Grothendieck construction of the monodromy functor $\mathrm{Fib}_E : \Pi_1(X) \to \mathrm{Set}$

$$\Pi_1(E) \;\simeq\; \int_{\Pi_1(X)} \mathrm{Fib}_E$$

whose

- objects are pairs $(x, \hat x)$ consisting of a point $x \in X$ and en element $\hat x \in \mathrm{Fib}_E(x)$;
- morphisms $[\hat \gamma] : (x, \hat x) \to (x', \hat x')$ are morphisms $[\gamma]: x \to x'$ in $\Pi_1(X)$ such that $\mathrm{Fib}_E([\gamma])(\hat x) = \hat x'$.

Proof. By the uniqueness of the path-lifting, lemma 2.7 and the very definition of the monodromy functor. ■

Proposition 2.14. *Let X be a path-connected topological space and let $E \overset{p}{\to} X$ be a covering space. Then the total space E is*

1. *path-connected precisely if the monodromy Fib_E is a transitive action;*
2. *simply connected precisely if the monodromy Fib_E is free action.*

Proof. By example 2.13. ■

Reconstruction

The following is a description of the reconstruction in terms of elementary point-set topology.

Definition 2.15. **(reconstruction of covering spaces from monodromy)**

Let

1. (X,τ) be a locally path-connected semi-locally simply connected topological space,
2. $\rho \in \mathrm{Set}^{\Pi_1(X)}$ a permutation representation of its fundamental groupoid.

Consider the disjoint union set of all the sets appearing in this representation

$$E(\rho) \;\coloneqq\; \underset{x \in X}{\sqcup} \rho(x)$$

For an open subset $U \subset X$ which is path-connected and for which every element of the fundamental group $\pi_1(U,x)$ becomes trivial under $\pi_1(U,x) \to \pi_1(X,x)$, and for $\hat x \in \rho(x)$ with $x \in U$ consider the subset

$$V_{U,\hat x} \coloneqq \left\{ \rho(\gamma)(\hat x) \;\vert\; x' \in U\,, \;\; \gamma \, \text{path from}\, x \,\text{to}\, x' \right\} \;\subset\; E(\rho)\,.$$

The collection of these defines a base for a topology (prop. 2.16 below). Write τ_ρ for the corresponding topology. Then

$$(E(\rho), \tau_\rho)$$

is a topological space. It canonically comes with the function

$$\array{ E(\rho) &\overset{p}{\longrightarrow}& X \\ \hat x \in \rho(x) &\mapsto& x }\,.$$

Finally, for

$$f \;\colon\; \rho_1 \longrightarrow \rho_2$$

a homomorphism of permutation representations, there is the evident induced

function

$$\begin{array}{ccc} E(\rho_1) & \xrightarrow{\mathrm{Rec}(f)} & E(\rho_2) \\ (\hat{x} \in \rho_1(x)) & \mapsto & (f_x(\hat{x}) \in \rho_2(x)) \end{array} \,.$$

Proposition 2.16. *The construction $\rho \mapsto E(\rho)$ in def. 2.15 is well defined and yields a covering space of X.*

Moreover, the construction $f \mapsto \mathrm{Rec}(f)$ yields a homomorphism of covering spaces.

Proof. First to see that we indeed have a topology, we need to check (by this prop.) that every point is contained in some base element, and that every point in the intersection of two base elements has a base neighbourhood that is still contained in that intersection.

So let $x \in X$ be a point. By the assumption that X is semi-locally simply connected there exists an open neighbourhood $U_x \subset X$ such that every loop in U_x on x is contractible in X. Moreover by the assumption that X is locally path-connected topological space, this contains a possibly smaller open neighbourhood $U'_x \subset U_x$ which is path connected. Moreover, as every subset of U_x, it still has the property that every loop in U'_x based on x is contractible as a loop in X. Now let $\hat{x} \in E$ be any point over x, then it is contained in the base open $V_{U'_x, x}$.

The argument for the base open neighbourhoods contained in intersections is similar.

Then we need to see that $p : E(\rho) \to X$ is a continuous function. Since taking pre-images preserves unions (this prop.), and since by semi-local simply connectedness every neighbourhood contains an open $U \subset X$ that labels a base open, it is sufficient to see that $p^{-1}(U)$ is a base open. But by the very assumption on U, there is a unique morphism in $\Pi_1(X)$ from any point $x \in U$ to any other point in U, so that ρ applied to these paths establishes a bijection of sets

$$p^{-1}(U) \;\simeq\; \underset{\hat{x} \in \rho(x)}{\sqcup} V_{U,\hat{x}} \;\simeq\; U \times \rho(x) \,,$$

thus exhibiting $p^{-1}(U)$ as a union of base opens.

Finally we need to see that this continuous function p is a covering projection, hence that every point $x \in X$ has a neighbourhood U such that $p^{-1}(U) \simeq U \times \rho(x)$. But this is again the case for those U all whose loops are contractible in X, by the above identification via ρ, and these exist around every point by semi-local simply-connetedness of X.

This shows that $p : E(\rho) \to X$ is a covering space. It remains to see that $\mathrm{Ref}(f) : E(\rho_1) \to E(\rho_2)$ is a homomorphism of covering spaces. Now by construction it is immediate that this is a function over X, in that this diagram commutes:

$$
\begin{array}{ccc}
E(\rho_1) & \overset{\mathrm{Rec}(f)}{\longrightarrow} & E(\rho_2) \\
& \searrow \quad \swarrow & \\
& X &
\end{array}
.
$$

So it only remains to see that $\mathrm{Ref}(f)$ is a continuous function. So consider $V_{U, y_2 \in \rho_2(x)}$ a base open of $E(\rho_2)$. By naturality of f its pre-image under $\mathrm{Rec}(f)$ is

$$
\mathrm{Rec}(f)^{-1}(V_{U, y_2 \in \rho_2(x)}) = \underset{y_1 \in f^{-1}(y_2)}{\sqcup} V_{U, y_1}
$$

and hence a union of base opens. ▮

3. Topological Galois theory

Fundamental theorem of covering spaces

Theorem 3.1. ***(fundamental theorem of covering spaces)***

Let X be a locally path-connected and semi-locally simply-connected topological space. Then the operations on

1. *extracting the monodromy Fib_E of a covering space E over X*
2. *reconstructing a covering space from monodromy $\mathrm{Rec}(\rho)$*

constitute an equivalence of categories

$$
\mathrm{Cov}(X) \underset{\underset{\mathrm{Fib}}{\longrightarrow}}{\overset{\mathrm{Rec}}{\longleftarrow}} \mathrm{Set}^{\Pi_1(X)} .
$$

Proof. Given $\rho \in \mathrm{Set}^{\Pi_1(X)}$ a permutation representation, we need to exhibit a natural isomorphism of permutation representations.

$$
\eta_\rho \,:\, \rho \longrightarrow \mathrm{Fib}(\mathrm{Rec}(\rho))
$$

First consider what the right hand side is like: By this def. of Rec and this def. of Fib we have for every $x \in X$ an actual equality

$$
\mathrm{Fib}(\mathrm{Rec}(\rho))(x) = \rho(x) .
$$

To similarly understand the value of $\mathrm{Fib}(\mathrm{Rec}(\rho))$ on morphisms $[\gamma] \in \Pi_1(X)$, let $\gamma : [0,1] \to X$ be a representing path in X. We find, by the Lebesgue number lemma as in the proof of this lemmapace#CoveringSpacePathLifting), a finite number of paths $\{\gamma_i\}_{i \in \{1,n\}}$ such that

1. regarded as morphisms $[\gamma_i]$ in $\Pi_1(X)$ they compose to $[\gamma]$:

$$
[\gamma] = [\gamma_n] \circ \cdots \circ [\gamma_2] \circ [\gamma_1]
$$

2. each γ_i factors through an open subset $U_i \subset X$ over which $\mathrm{Rec}(\rho)$ trivializes.

Hence by functoriality of $\mathrm{Fib}(\mathrm{Rec}(\rho))$ it is sufficient to understand its value on these paths γ_i. But on these we have again by direct unwinding of the definitions that

$$\mathrm{Fib}(\mathrm{Rec}(\rho))([\gamma_i]) = \rho([\gamma_i]) \; .$$

This means that if we take

$$\eta_\rho(x) : \rho(x) \overset{=}{\longrightarrow} \mathrm{Fib}(\mathrm{Rec}(\rho))$$

to be the above identification, then this is a natural transformation and hence in a particular a natural isomorphism, as required.

Conversely, given $E \in \mathrm{Cov}(X)$ a covering space, we need to exhibit a natural isomorphism of covering spaces of the form

$$\epsilon_E \;:\; \mathrm{Rec}(\mathrm{Fib}(E)) \longrightarrow E \; .$$

Again by this def. of Rec and this def. of Fib the underlying set of $\mathrm{Rec}(\mathrm{Fib}(E))$ is actually equal to that of E, hence it is sufficient to check that this identity function on underlying sets is a homeomorphism of topological spaces.

By the assumption that X is locally path-connected and semi-locally simply connected, it is sufficient to check for $U \subset X$ an open path-connected subset and $x \in X$ a point with the property that $\pi_1(U,x) \to \pi_1(X,x)$ lands is constant on the trivial element, that the open subsets of E of the form $U \times \{\hat x\} \subset p^{-1}(U)$ form a basis for the topology of $\mathrm{Rec}(\mathrm{Fib}(E))$. But this is the case by definition of Rec.

This proves the equivalence.

(Notice that the assumption of local path-connectedness and semi-local simply-connectedness of X is used only to guarantee that the functor Rec exists in the first place.) ▮

Applications

Proposition 3.2. ***(fundamental group of the circle is the integers)***

The fundamental group π_1 of the circle S^1 is the additive group of integers:

$$\pi_1(S^1) \overset{\simeq}{\longrightarrow} \mathbb{Z}$$

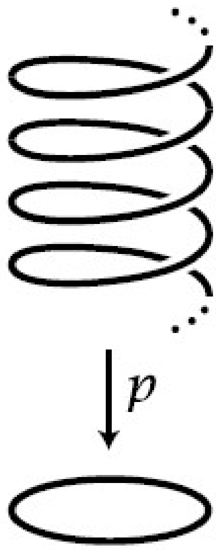
and the isomorphism is given by assigning winding number.

Here in the context of topological homotopy theory the circle S^1 is the topological subspace $S^1 = \{x \in \mathbb{R}^2 \,\vert\, x_1^2 + x_2^2 = 1\} \subset \mathbb{R}^2$ of the Euclidean plane with its metric topology, or any topological space of the same homotopy type. More generally, the circle in question is, as a homotopy type, the homotopy pushout

$$S^1 \simeq \ast \coprod_{\ast \sqcup \ast} \ast \; ,$$

hence the homotopy type with the universal property that it makes a homotopy commuting diagram of the form

$$\begin{tikzcd} \ast \sqcup \ast \arrow[r] \arrow[d] \arrow[dr, phantom, "\swarrow"] & \ast \arrow[d] \\ \ast \arrow[r] & S^1 \end{tikzcd} .$$



Proof. The universal covering space $\widehat{S^1}$ of S^1 is the real line (by this example):

$$p \coloneqq (\cos(2\pi(-)), \sin(2\pi(-))) \,:\, \mathbb{R}^1 \longrightarrow S^1 \,.$$

Since the circle is locally path-connected (this example) and semi-locally simply connected (this example) the fundamental theorem of covering spaces applies and gives that the automorphism group of $\mathbb{R}^1$ over S^1 equals the automorphism group of its monodromy permutation representation:

$$\mathrm{Aut}_{\mathrm{Cov}(S^1)}(\mathbb{R}^1) \;\simeq\; \mathrm{Aut}_{\pi_1(S^1)\mathrm{Set}}(\mathrm{Fib}_{S^1}) \,.$$

Moreover, as a corollary of the fundamental theorem of covering spaces we have that the monodromy representation of a universal covering space is given by the action of the fundamental group $\pi_1(S)$ on itself (this prop.).

But the automorphism group of any group regarded as an action on itself by left multiplication is canonically isomorphic to that group itself (by this example), hence we have

$$\mathrm{Aut}_{\pi_1(S^1)\mathrm{Set}}(\mathrm{Fib}_{S^1}) \;\simeq\; \mathrm{Aut}_{\pi_1(S^1)\mathrm{Set}}(\pi_1(S^1)) \;\simeq\; \pi_1(S^1) \,.$$

Therefore to conclude the proof it is now sufficient to show that

$$\mathrm{Aut}_{\mathrm{Cov}(S^1)}(\mathbb{R}^1) \simeq \mathbb{Z} \,.$$

To that end, consider a homeomorphism of the form

$$\begin{tikzcd} \mathbb{R}^1 \arrow[rr, "f", "\simeq"'] \arrow[dr, "p"'] & & \mathbb{R}^1 \arrow[dl, "p"] \\ & S^1 & \end{tikzcd} .$$

Let $s \in S^1$ be any point, and consider the restriction of f to the fibers over the complement:

$$\begin{tikzcd} p^{-1}(S^1 \setminus \{s\}) \arrow[rr, "f", "\simeq"'] \arrow[dr, "p"'] & & p^{-1}(S^1 \setminus \{s\}) \arrow[dl, "p"] \\ & S^1 \setminus \{s\} & \end{tikzcd} .$$

By the covering space property we have (via this example) a homeomorphism

$$p^{-1}(S^1 \setminus \{s\}) \simeq (0,1) \times \mathrm{Disc}(\mathbb{Z}) \,.$$

Therefore, up to homeomorphism, the restricted function is of the form

$$\begin{array}{ccc} (0,1)\times \mathrm{Disc}(\mathbb{Z}) & \underoverset{\simeq}{f}{\longrightarrow} & (0,1)\times \mathrm{Disc}(\mathbb{Z}) \\ & {}_{\mathllap{\mathrm{pr}_1}}\searrow & \swarrow_{\mathrlap{\mathrm{pr}_1}} \\ && (0,1) \end{array} \,.$$

By the universal property of the product topological space this means that f is equivalently given by its two components

$$(0,1) \times \mathrm{Disc}(\mathbb{Z}) \overset{\mathrm{pr}_1 \circ f}{\longrightarrow} (0,1) \qquad (0,1) \times \mathrm{Disc}(\mathbb{Z}) \overset{\mathrm{pr}_2 \circ f}{\longrightarrow} \mathrm{Disc}(\mathbb{Z}) \,.$$

By the commutativity of the above diagram, the first component is fixed to be pr_1. Moreover, by the fact that $\mathrm{Disc}(\mathbb{Z})$ is a discrete space it follows that the second component is a locally constant function (by this example). Therefore, since the product space with a discrete space is a disjoint union space (via this example)

$$(0,1) \times \mathrm{Disc}(\mathbb{Z}) \simeq \underset{n \in \mathbb{Z}}{\sqcup} (0,1)$$

and since the disjoint summands $(0,1)$ are connected topological spaces (this example), it follows that the second component is a constant function on each of these summands (by this example).

Finally, since every function out of a discrete topological space is continuous, it follows in conclusion that the restriction of f to the fibers over $S^1 \setminus \{s\}$ is entirely encoded in an endofunction of the set of integers

$$\phi \;:\; \mathbb{Z} \to \mathbb{Z}$$

by

$$\begin{array}{ccc} S^1 \setminus \{s\} \times \mathrm{Disc}(\mathbb{Z}) & \overset{f}{\longrightarrow} & S^1 \setminus \{s\} \times \mathrm{Disc}(\mathbb{Z}) \\ (t,k) &\mapsto& (t, \phi(k)) \end{array} \,.$$

Now let $s' \in S^1$ be another point, distinct from s. The same analysis as above applies now to the restriction of f to $S^1 \setminus \{s'\}$ and yields a function

$$\phi' \;:\; \mathbb{Z} \longrightarrow \mathbb{Z} \,.$$

Since

$$\left\{ p^{-1}(S^1 \setminus \{s\}) \subset \mathbb{R}^1, \, p^{-1}(S^1 \setminus \{s'\}) \subset \mathbb{R}^1 \right\}$$

is an open cover of $\mathbb{R}^1$, it follows that f is unqiuely fixed by its restrictions to these two subsets.

Now unwinding the definition of p shows that the condition that the two

restrictions coincide on the intersection $S^1 \setminus \{s, s'\}$ implies that there is $n \in \mathbb{Z}$ such that $\phi(k) = k + n$ and $\phi'(k) = k + n$.

This shows that $\mathrm{Aut}_{\mathrm{Cov}(S^1)}(\mathbb{R}^1) \simeq \mathbb{Z}$. ▮

This concludes the introduction to basic homotopy theory.

For introduction to more general and abstract homotopy theory see at *Introduction to Homotopy Theory*.

An incarnation of homotopy theory in linear algebra is *homological algebra*. For introduction to that see at *Introduction to Homological Algebra*.

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4. References

A textbook account is in

- Tammo tom Dieck, sections 2 an 3 of *Algebraic Topology*, EMS 2006 (pdf)

Lecture notes include

- Jesper Møller, *The fundamental group and covering spaces* (2011) (pdf)

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