

MATH 480: HOMOTOPY THEORY

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1. MOTIVATION/BACKGROUND

Lecture 1.

The things that mathematicians care about can often be distinguished by two qualities: *existence* and *uniqueness*. That is, suppose a mathematician thinks of some concept X . There are two obvious questions to ask:

- Does such a concept X actually exist? If so, can we explicitly construct it?
- If a concept X exists, is it unique? If it isn't unique, can we classify all such types of concepts X ?

In this course, we will be studying topological spaces. Recall that a *topological space* is a set X together with a collection \mathcal{T} of subsets, called the *topology*, such that:

- $\emptyset, X \in \mathcal{T}$,
- for any collection $\{U_i\}_{i \in I} \subseteq \mathcal{T}$ we have that $\bigcup_{i \in I} U_i \in \mathcal{T}$, and
- for any finite collection $\{U_i\}_{i=1}^n$ we have that $\bigcap_{i=1}^n U_i \in \mathcal{T}$.

We will refer to the elements of \mathcal{T} as *open sets*. It is not hard to see that topological spaces exist.

Example 1.1.

- If X is any metric space, then one can place a topology on X by letting

$$\mathcal{T} = \{B_\varepsilon(x) : x \in X, \varepsilon > 0\}.$$

In particular, \mathbb{R}^n and \mathbb{C}^n are topological spaces under the usual metric.

- If Y is a subset of any topological space X , then Y inherits a subspace topology, where the open sets in Y are just the open sets in X which intersect Y . In particular, the *n-sphere*

$$S^n = \{x \in \mathbb{R}^{n+1} : \|x\| = 1\} \subseteq \mathbb{R}^{n+1}$$

is a topological space.

- If X is any set, then there are always two ways to topologize X : the *discrete topology* has open sets every possible subset of X , and the *trivial topology* has open sets just \emptyset and X .

Well, since topological spaces exist, and we can explicitly construct them, let's move on to the second point. Can we *classify* topological spaces?

There is a strict way to attempt to approach this question: classify spaces up to *homeomorphism*. Recall that a *continuous function* $f : X \rightarrow Y$ is a function such that the preimage $f^{-1}(U) \subseteq X$ of any open set $U \subseteq Y$ is open, and a *homeomorphism* is a continuous function such that there exists another continuous function $g : Y \rightarrow X$, which we'll call the *inverse*, such that

$$g \circ f = \text{id}_X : X \rightarrow X, \quad f \circ g = \text{id}_Y : Y \rightarrow Y.$$

⚠ Warning ⚠ 1.2. It is not enough for a continuous function to be a bijection to be a homeomorphism.

Exercise 1.3. Construct a continuous bijection which is not a homeomorphism.

It is not an easy task to determine whether or not two random spaces are homeomorphic. If we want to be really general and consider all topological spaces (or at least most of them), then classifying them *up to homeomorphism* seems a little out of reach.

There are two clear directions to move forward from this obstacle. On the one hand, we can put more structure on our spaces and impose a stricter notion of equivalence. For example, we could only consider *manifolds*, which are topological spaces that are locally modeled by \mathbb{R}^n , or we could consider *differentiable manifolds*, which have structures amenable to the tools of calculus, or we could consider *varieties*, which are the zero-loci of systems of polynomial equations. Each of these types of spaces has a more fine-tuned notion of equivalence which allows us to better classify that type of space.

This direction will not be the focus of this course. Instead, we will *loosen* our notion of equivalence and study spaces up to *homotopy equivalence*. If you didn't think that topology was flexible enough, what with the open interval being homeomorphic to the real number line, well then get ready for some real gymnastics.

Let $f, g : X \rightarrow Y$ be continuous maps. A *homotopy* between f and g is a continuous function

$$H : X \times I \rightarrow Y$$

where $I = [0, 1]$ denotes the unit interval (which we think of as a time parameter), such that at time $t = 0$, we have $H(x, 0) = f(x)$, and at time $t = 1$, we have $H(x, 1) = g(x)$. We will often use the notation $f \simeq g$ if there is a homotopy from f to g and say that they are *homotopic*.

Example 1.4. Define two continuous maps $f, g : \mathbb{R} \rightarrow \mathbb{R}^2$ by

$$f(x) = (x, x^2), \quad g(x) = (x, x).$$

We can define a homotopy between f and g quite easily: let $H : \mathbb{R} \times I \rightarrow \mathbb{R}^2$ be defined by

$$H(x, t) = (x, x^2 - tx^2 + tx).$$

Then $H(x, 0) = (x, x^2) = f(x)$ and $H(x, 1) = (x, x) = g(x)$. This can be seen graphically here <https://www.desmos.com/calculator/acoupulhy1>.

Exercise 1.5. Show that the notion of homotopy defines an equivalence relation on the set of continuous functions from X to Y by showing the following:

- If $f : X \rightarrow Y$ is any function, then there is a homotopy $H : X \times I \rightarrow Y$ from f to itself.
- If $H : X \times I \rightarrow Y$ is a homotopy from f to g , then there is a homotopy $H' : X \times I \rightarrow Y$ from g to f .
- If $f, g, h : X \rightarrow Y$ are continuous functions such that $f \simeq g$ and $g \simeq h$, then there is a homotopy $H : X \times I \rightarrow Y$ from f to h .

A *homotopy equivalence* is a continuous function $f : X \rightarrow Y$ such that there exists another continuous function $g : Y \rightarrow X$ such that

$$g \circ f \simeq \text{id}_X : X \rightarrow X, \quad f \circ g \simeq \text{id}_Y : Y \rightarrow Y.$$

We will often write that $X \simeq Y$ if X is homotopy equivalent to Y .

Example 1.6. Consider the functions $f, g : \mathbb{R} \rightarrow \mathbb{R}^2$ from the previous example. Essentially the same homotopy between the functions f and g shows that the subspaces

$$\text{im}(f), \text{im}(g) \subseteq \mathbb{R}^2,$$

i.e. the graphs of the functions

Notice that this is very similar to the notion of homeomorphism; we have just required that the compositions be *homotopic* to the identity instead of equal. And indeed, this is a weaker notion.

Proposition 1.7. Let $f : X \rightarrow Y$ be a homeomorphism. Then f is a homotopy equivalence.

Proof. Since f is a homeomorphism, there is a continuous function $g : Y \rightarrow X$ such that $g \circ f = \text{id}_X$ and $f \circ g = \text{id}_Y$. Define a function $H : X \times I \rightarrow X$ by $H(x, t) = (g \circ f)(x)$. This is continuous: if $U \subseteq X$ is open, then

$$H^{-1}(U) = (g \circ f)^{-1}(U) \times I = (\text{id}_X)^{-1}(U) \times I = U \times I.$$

This is open in the product topology on $X \times I$. Moreover, $H(x, 0) = (g \circ f)(x)$, and $H(x, 1) = (g \circ f)(x) = \text{id}_X(x) = x$, so H is a homotopy between $g \circ f$ and id_X . The same argument works to show that $f \circ g \simeq \text{id}_Y$. \square

To illustrate how loose of a notion homotopy equivalence is, consider the following example.

Example 1.8. Let $\overline{\mathbb{D}^n}$ be the closed unit disc in \mathbb{R}^n , regardless of n , and let $*$ denote, well, a point. It is not hard to see that $\overline{\mathbb{D}^n}$ is homotopy equivalent to $*$: let $f : \overline{\mathbb{D}^n} \rightarrow *$ be the only map possible (which sends every point in the disc to the point) and let $g : * \rightarrow \overline{\mathbb{D}^n}$ send $*$ to 0 (or honestly to any point in the disc). Then we have

$$f \circ g : * \rightarrow *, \quad (f \circ g)(*) = *,$$

and

$$g \circ f : \overline{\mathbb{D}^n} \rightarrow \overline{\mathbb{D}^n}, \quad (g \circ f)(x) = g(*) = 0.$$

It is worth checking (and not hard) that

$$H : * \times I \rightarrow *, \quad H(*, t) = *,$$

and

$$H' : \mathbb{D}^n \times I \rightarrow \mathbb{D}^n, \quad H(x, t) = t \cdot x$$

give the desired homotopy equivalences $g \circ f \simeq \text{id}_{\mathbb{D}^n}$ and $f \circ g \simeq \text{id}_*$.

Something the above example shows is: if you had any preconceived notion of dimension, just know that homotopy equivalences couldn't care less! We will call a space which is homotopy equivalent to a point *contractible*. Notice that the above argument also shows that \mathbb{R}^n itself is contractible.

Warning 1.9. It is **NOT TRUE** that if X is contractible and $Y \subseteq X$ is a subspace, then Y is contractible.

It turns out that, except in some particularly cherry-picked examples like the one above, it is still not very easy to determine if two randomly selected spaces are homotopy equivalent. There are a lot of ways to try and address this problem; one of the ways we will address it is by introducing *invariants* known as *homotopy groups*.

Lecture 2.

We will explore this more thoroughly throughout the course; for now, we will say that the n^{th} homotopy group of a space, denoted $\pi_n(X)$, is a calculable invariant which roughly measures the number of n -dimensional holes in X . The key point is that instead of telling us when two spaces are homotopy equivalent, these groups are a nice way to tell when two spaces are NOT homotopy equivalent!

Theorem 1.10. *Suppose that for some $n > 0$, $\pi_n(X) \neq \pi_n(Y)$. Then X is not homotopy equivalent to Y .*

So, if we can develop tools to compute homotopy groups, then we can try to differentiate spaces. Again, if this were easy, then there would be no field of homotopy theory. But it is in the surprising complexity of this problem that some really beautiful mathematics has been discovered!

Let's look at our favorite (or at least my favorite) spaces: the spheres S^n . These spaces are very simple to define, and for the most part we can even imagine what they look like (or at least pretend). However, the homotopy groups of spheres have a well earned reputation for being chaotic, full of mystery, and are wildly unpredictable. Table 1 has a few examples.

$\pi_i(S^n)$	S^1	S^2	S^3	S^4	S^5	S^6	S^7
$\pi_1(-)$	\mathbb{Z}	0	0	0	0	0	0
$\pi_2(-)$	0	\mathbb{Z}	0	0	0	0	0
$\pi_3(-)$	0	\mathbb{Z}	\mathbb{Z}	0	0	0	0
$\pi_4(-)$	0	$\mathbb{Z}/2$	$\mathbb{Z}/2$	\mathbb{Z}	0	0	0
$\pi_5(-)$	0	$\mathbb{Z}/2$	$\mathbb{Z}/2$	$\mathbb{Z}/2$	\mathbb{Z}	0	0
$\pi_6(-)$	0	$\mathbb{Z}/12$	$\mathbb{Z}/12$	$\mathbb{Z}/2$	$\mathbb{Z}/2$	\mathbb{Z}	0
$\pi_7(-)$	0	$\mathbb{Z}/2$	$\mathbb{Z}/2$	$\mathbb{Z} \times \mathbb{Z}/12$	$\mathbb{Z}/2$	$\mathbb{Z}/2$	\mathbb{Z}
$\pi_8(-)$	0	$\mathbb{Z}/2$	$\mathbb{Z}/2$	$\mathbb{Z}/2 \times \mathbb{Z}/2$	$\mathbb{Z}/24$	$\mathbb{Z}/2$	$\mathbb{Z}/2$
$\pi_9(-)$	0	$\mathbb{Z}/3$	$\mathbb{Z}/3$	$\mathbb{Z}/2 \times \mathbb{Z}/2$	$\mathbb{Z}/2$	$\mathbb{Z}/24$	$\mathbb{Z}/2$
$\pi_{10}(-)$	0	$\mathbb{Z}/15$	$\mathbb{Z}/15$	$\mathbb{Z}/24 \times \mathbb{Z}/3$	$\mathbb{Z}/2$	0	$\mathbb{Z}/24$

TABLE 1. Some homotopy groups of spheres. What could it all mean?

We'll talk later about what these particular values mean, but maybe you can already start to see some patterns. Here are a few observations that I'll point out:

- The only non-trivial homotopy group of the circle S^1 is $\pi_1(S^1) = \mathbb{Z}$. Topologically this is like saying that there are no "higher dimensional hole" in S^1 .
- If $n < k$, then $\pi_n(S^k) = 0$. Topologically, this is like saying there smallest hole in S^k is of dimension k .
- At least in the values depicted here, we see that $\pi_n(S^n) = \mathbb{Z}$.

- For $k > 1$, we do **not** see that $\pi_n(S^k) = 0$ for $n > k$, as opposed to the case for S^1 . So, this is saying that there are “high-dimensional holes” in S^k .
- The values given are *almost* all finite.

We will try our best to understand and more rigorously study some of these concepts throughout this course.

Another feature of homotopy theory, which is another core tenant of this course, is that there are operations on spaces themselves that give us relations between homotopy groups and can inform us about homotopy equivalences. If homotopy groups are an assignment of algebra to a topological problem, then space-level operations are an *extraction* of algebra from within a topological problem. To avoid getting too side-winded, let me just give a brief example.

Example 1.11. Consider the torus \mathbb{T} and the 2-sphere S^2 . Both of these objects live in \mathbb{R}^3 and seem to have a “hole”. How can we tell if they are homotopy equivalent or not without explicitly trial-and-error-ing our way through this problem?

Another way to write the torus is as $\mathbb{T} = S^1 \times S^1$; that is, we can decompose the torus as a product of two better understood spaces (at least, if we accept the above table). This is very nice: homotopy groups *respect products*. That is $\pi_n(X \times Y) = \pi_n(X) \times \pi_n(Y)$. In our case, this tells us that

$$\pi_1(\mathbb{T}) = \pi_1(S^1) \times \pi_1(S^1) = \mathbb{Z} \times \mathbb{Z}.$$

But our above table says that $\pi_1(S^2) = 0$, so there can be no homotopy equivalence between the torus and the 2-sphere.

One may organize this course into 3 different themes:

- Attaching algebraic invariants to topological spaces;
- Studying algebraic phenomena exhibited by topological spaces;
- Understanding the passage from topology to algebra and vice versa.

This last point really means: we will develop and use the tools of category theory to study the homotopy theory of topological spaces.

2. THE FUNDAMENTAL GROUP

Lecture 3.

Let X be a topological space. A *path* in X is a continuous function $\gamma : I \rightarrow X$, where $I \subseteq \mathbb{R}$ is the closed unit interval. Two paths $\gamma, \varphi : I \rightarrow X$ are *composable* if $\gamma(1) = \varphi(0)$, i.e. if one ends at the starting point of the other. Define their *product* as the path $\varphi \cdot \gamma : I \rightarrow X$ given by

$$\varphi \cdot \gamma(t) = \begin{cases} \gamma(2t) & t \in [0, \frac{1}{2}] \\ \varphi(2t - 1) & t \in [\frac{1}{2}, 1]. \end{cases}$$

Notice that we should read function product from right to left, just as we read function composition. Not everyone follows this convention, so beware!

Paths give us a way to “feel out” the structure of a space. We only want to work with paths up to homotopy in this class, as we want to work with everything up to homotopy, but we encounter a bit of a snag.

Exercise 2.1. Let X be path connected. If $\gamma : I \rightarrow X$ and $\varphi : I \rightarrow X$ are any paths, then there is a homotopy $H : I \times I \rightarrow X$ from γ to φ . (**Hint:** If X is path-connected, then there is a path from $\gamma(0)$ to $\varphi(0)$. Use this path to go from γ to φ .)

This implies that, so as not to make everything trivial in a path-connected space, we should make a slight more refined notion of homotopy for paths. A *path homotopy* between two paths $\gamma, \varphi : I \rightarrow X$ is a homotopy $H : I \times I \rightarrow X$ from γ to φ such that

$$H(0, t) = \gamma(0) = \varphi(0), \quad H(1, t) = \gamma(1) = \varphi(1)$$

In other words, the ends of the interval I are sent to the same points in X by both γ and φ , and for any time t_0 , the path $f_{t_0} : I \rightarrow X$ given by $f(s) = F(t_0, s)$ also sends the ends of I to the same points as γ and φ do. Thus a path homotopy only exists for particular paths which share endpoints.

Just as homotopy equivalence defines an equivalence relation, so too does path homotopy equivalence. We will let $[f]$ denote the *path homotopy class* of f ; these are the paths into X which are path-homotopic to f .

A path is called a *loop* if we have that $\gamma(0) = \gamma(1)$. Note that if $\gamma : I \rightarrow X$ is a loop, then since we can view S^1 as the quotient space $I/0 \sim 1$, we can factor γ uniquely through the circle:

$$\begin{array}{ccc} I & \xrightarrow{\gamma} & X \\ \downarrow & \nearrow \tilde{\gamma} & \\ S^1 & & \end{array}$$

The universal property of the quotient implies that $\tilde{\gamma}$ is continuous since γ is. In fact, this factorization characterizes loops! A path is a loop if and only if the above diagram commutes.

We come to our first invariant. Let (X, x_0) be a based space, which is just a topological space X with a chosen basepoint x_0 . Note that a morphism of based spaces is just a continuous morphism which sends basepoint to basepoint. The *fundamental group* of X based at x_0 , denoted $\pi_1(X, x_0)$, is the set of path classes of loops in X based at x_0 . In other words,

$$\pi_1(X, x_0) = \{[f] \mid f : (S^1, 1) \rightarrow (X, x_0) \text{ based map}\}.$$

There is a constant path $c : S^1 \rightarrow X$ where $c(t) = x_0$ for all $t \in S^1$. In general, though, it takes some work to determine what the actual loops are in a space.

Exercise 2.2. Show that re-parameterizing paths doesn't actually do anything to the fundamental group. That is, let $\gamma : S^1 \rightarrow X$ be some loop. We can lift this along the quotient map $I \rightarrow S^1$ to a map $\tilde{\gamma} : I \rightarrow X$ where $\tilde{\gamma}(0) = \tilde{\gamma}(1)$. Let $\varphi : I \rightarrow I$ be any continuous map where $\varphi(0) = 0$ and $\varphi(1) = 1$. Show that there is a path homotopy from $\tilde{\gamma}$ to $\tilde{\gamma} \circ \varphi$.

The naming of $\pi_1(X, x_0)$ is not accidental. For a path $\gamma : I \rightarrow X$, let $\gamma^{\text{rev}} : I \rightarrow X$ be the path which "does γ in reverse". That is, $\gamma^{\text{rev}}(t) = \gamma(1 - t)$.

Theorem 2.3. Let $\gamma : p \rightarrow q$ be a path in a space X , and let $\varphi, \psi : I \rightarrow X$ be any paths.

- $[c_p] \cdot [\gamma] = [\gamma] \cdot [c_q] = [\gamma]$
- $[\gamma][\gamma^{\text{rev}}] = [c_p]$ and $[\gamma^{\text{rev}}][\gamma] = [c_q]$
- Whenever defined, we have $[f] \cdot ([g] \cdot [h]) = ([f] \cdot [g]) \cdot [h]$.

Corollary 2.4. The set $\pi_1(X, x_0)$ forms a group under path composition, with identity given by $[c_{x_0}]$.

Warning 2.5. The fundamental group need not be abelian! That is, there are based spaces (X, x_0) and loops $[\gamma], [\varphi] \in \pi_1(X, x_0)$ such that $[\varphi] \cdot [\gamma] \neq [\gamma] \cdot [\varphi]$.

The choice of basepoint is very important here! For example, take $X = Y \amalg \mathbb{R}$, where Y is any space such that $\pi_1(Y, y_0) \neq 0$ for some point $y_0 \in Y$. Then

$$\pi_1(X, y_0) \cong \pi_1(Y, y_0) \neq 0,$$

since any loop in X which is based at a point in Y must be entirely contained in Y as the image of a connected set is connected. For the same argument, if $t \in \mathbb{R}$ is any point, then any loop $S^1 \rightarrow X$ based at t must have image entirely contained in \mathbb{R} . But we have already seen that $\mathbb{R} \simeq *$, which implies that $\pi_1(\mathbb{R}, t) = 0$. Thus, we also have that $\pi_1(X, t) = 0$.

Lecture 4.

However, things are much nicer in path-connected spaces.

Proposition 2.6. Suppose that X is path-connected, $p, q \in X$ are any points, and $\gamma : p \rightarrow q$ is a path. Define a function

$$\Phi : \pi_1(X, p) \rightarrow \pi_1(X, q), \quad \Phi([\varphi]) = [\gamma] \cdot [\varphi] \cdot [\gamma^{\text{rev}}].$$

This is an isomorphism of groups.

Proof. First, we must check that this is a group homomorphism. Observe:

$$\begin{aligned}\Phi([f] \cdot [g]) &= [\gamma] \cdot [f] \cdot [g] \cdot [\gamma^{\text{rev}}] \\ &= [\gamma] \cdot [f] \cdot [\gamma^{\text{rev}}] \cdot [\gamma] \cdot [g] \cdot [\gamma^{\text{rev}}] \\ &= \Phi([f]) \cdot \Phi([g]).\end{aligned}$$

For injectivity, suppose that $\Phi([f]) = 0 = [c_q]$. Expanding out our function, this tells us that

$$\Phi([f]) = [\gamma] \cdot [f] \cdot [\gamma^{\text{rev}}] = [c_q].$$

Multiplying on the left by $[\gamma^{\text{rev}}]$ and on the right by $[\gamma]$, we obtain

$$[\gamma^{\text{rev}}] \cdot [\gamma] \cdot [f] \cdot [\gamma^{\text{rev}}] \cdot [\gamma] = [\gamma^{\text{rev}}] \cdot [c_q] \cdot [\gamma].$$

Since $[\gamma] \cdot [\gamma^{\text{rev}}] = [c_q]$, and since $[c_q]$ is the identity of $\pi_1(X, q)$, we can rewrite our equation as

$$[f] = [c_p],$$

giving injectivity.

I will leave surjectivity as an exercise. □

If (X, x_0) is path-connected, we will simply refer to its fundamental group by $\pi_1(X)$, as the above proposition proves that this is independent of basepoint.

The next proposition gives us a way to pass from topology to algebra at the level of functions. Namely, continuous maps of based spaces induce group homomorphisms of fundamental groups.

Proposition 2.7. *Let $f : (X, x_0) \rightarrow (Y, y_0)$ be a map of based spaces. Then the function*

$$f_* : \pi_1(X, x_0) \rightarrow \pi_1(Y, y_0), \quad f_*([\gamma]) = [f \circ \gamma]$$

is a group homomorphism. Moreover:

- *if we have $g : (Y, y_0) \rightarrow (Z, z_0)$ continuous, then*

$$(g_* \circ f_*)([\gamma]) = (g \circ f)_*([\gamma])$$

- *if $\text{id}_X : (X, x_0) \rightarrow (X, x_0)$ is the identity map, then*

$$(\text{Id}_X)_* = \text{Id}_{\pi_1(X, x_0)}$$

Proof. Homework. □

Let's look at some examples!

Example 2.8.

- Suppose that $X \simeq *$ is contractible and $x_0 \in X$ is any point. Then there is a homotopy $H : X \times I \rightarrow X$ witnessing $\text{id}_X \simeq c_{x_0}$. We can use this homotopy to show that any loop $f : S^1 \rightarrow X$ is nullhomotopic. Let $F : S^1 \times I \rightarrow X$ be defined by

$$F(r, t) = H(f(r), t).$$

This is continuous, as another way to write this function is as $F = H \circ (f \times \text{id}_I)$. Moreover,

$$F(r, 0) = H(f(r), 0) = \text{id}_X(f(r)) = f(r),$$

and

$$F(r, 1) = H(f(r), 1) = c_{x_0}(f(r)) = x_0.$$

Thus, if X is any contractible space, then $\pi_1(X, x_0) = 0$ for any basepoint X .

- More generally, and this is slightly more work to show, if $f : X \rightarrow Y$ is a homotopy equivalence, then the induced map $f_* : \pi_1(X, x_0) \rightarrow \pi_1(Y, f(x_0))$ is an isomorphism of groups. Thus, homotopy equivalent spaces have the same fundamental groups.

Next, we will prove our first big theorem, and make our first nontrivial fundamental group computation.

Theorem 2.9. *The fundamental group of the circle is*

$$\pi_1(S^1) \cong \mathbb{Z}$$

This will require a bit of work. First, define a path $\omega_n : I \rightarrow S^1$ by

$$\omega_n(t) = e^{2\pi i \cdot nt},$$

where $n \in \mathbb{Z}$ and we are viewing $S^1 \subseteq \mathbb{C}$. This path is a loop, since $e^0 = e^{2\pi i \cdot n} = 1$ for all $n \in \mathbb{Z}$. Geometrically, this is the loop which winds around the circle n -times.

Lecture 5.

It is straightforward to see that $[\omega_n] \cdot [\omega_m] = [\omega_{n+m}]$. This simple observation is really useful: it implies that the function

$$\phi : \mathbb{Z} \rightarrow \pi_1(S^1, 1), \quad \phi(n) = [\omega_n]$$

is a group homomorphism. Our goal now is to show that ϕ is an isomorphism.

The intuition here is that the collection of maps $\{\omega_n\}_{n \in \mathbb{Z}}$ acts a lot like the integers, where the number $n \in \mathbb{Z}$ corresponds to going around the circle n -times counter-clockwise. The point of our calculation is that that is all that can happen.

- Showing the map ϕ is surjective says that every loop in S^1 looks like “going around the circle” some number of times.
- Showing the map ϕ is injective says that going around the loop n -times and going around the loop m -times is never somehow equivalent in $\pi_1(S^1, 1)$ when $n \neq m$.

The “reason” why ϕ is an isomorphism is that, locally, S^1 just looks like the real numbers \mathbb{R} . Since $\mathbb{R} \simeq *$, meaning $\pi_1(\mathbb{R}, 1) = 0$, there can be no weird local behavior of S^1 that obfuscates our argument.

There is a continuous map $p : \mathbb{R} \rightarrow S^1$ which will feature very heavily in these arguments. This map is defined by

$$p(t) = e^{2\pi i \cdot t},$$

which we can geometrically think of as “winding the real numbers around S^1 ”. Consider again the map $\omega_n : I \rightarrow S^1$. We can **lift** this map along p to a map $\tilde{\omega}_n : I \rightarrow \mathbb{R}$ where

$$\tilde{\omega}_n(t) = n \cdot t.$$

By “lift along p ”, I mean that the maps ω_n and p fit into a diagram of the form:

$$\begin{array}{ccc} & & \mathbb{R} \\ & & \downarrow p \\ I & \xrightarrow{\omega_n} & S^1 \end{array}$$

and the map $\tilde{\omega}_n$ fills in the triangle and makes the diagram commute:

$$\begin{array}{ccc} & & \mathbb{R} \\ & \nearrow \tilde{\omega}_n & \downarrow p \\ I & \xrightarrow{\omega_n} & S^1 \end{array}$$

In fact, the existence of a lift is not unique to the paths γ_n . All paths in S^1 lift to \mathbb{R} , and they lift *uniquely* as soon as we specify any value.

Proposition 2.10 (Path lifting). *Let $f : I \rightarrow S^1$ be any path with $\gamma(0) = x \in S^1$. Let $\tilde{x} \in p^{-1}(x)$ be any point in the fiber over x . Then there is a unique lift $\tilde{f} : I \rightarrow \mathbb{R}$ such that $\tilde{f}(0) = \tilde{x}$ and $f = p \circ \tilde{f}$.*

Exercise 2.11. Prove the above proposition. Notice that as there are infinitely many points in the fiber $p^{-1}(x) \subseteq \mathbb{R}$ (in fact if $t \in p^{-1}(x)$ then $t + n \in p^{-1}(x)$ for any $n \in \mathbb{Z}$), the choice of lift \tilde{f} is certainly not unique unless we specify $\tilde{f}(0)$.

Path lifting is nice. Even stronger is that we can lift entire homotopies from S^1 to \mathbb{R} .

Proposition 2.12 (Homotopy path lifting). *Let $H : I \times I \rightarrow S^1$ be a path homotopy from $H(s, 0)$ and $H(s, 1)$, and let $x = H(0, t)$ for any $t \in I$. Let $\tilde{x} \in p^{-1}(x)$. Then there is a unique lift $\tilde{H} : I \times I \rightarrow \mathbb{R}$ such that $H = p \circ \tilde{H}$ and $\tilde{H}(0, t) = \tilde{x}$ for all $t \in I$.*

Remark 2.13. We will not prove the above proposition. For reference, see section 1.1 of Hatcher’s book.

Using these propositions, we will prove that $\pi_1(S^1, 1) \cong \mathbb{Z}$.

First, we show that ϕ is surjective. Let $\gamma : (I, 0) \rightarrow (S^1, 1)$ be a loop. **Path lifting** implies that there is a unique lift $\tilde{\gamma} : (I, 1) \rightarrow (\mathbb{R}, 0)$ such that $\tilde{\gamma}(0) = 0$.

$$\begin{array}{ccc} & \mathbb{R} & \\ & \nearrow \tilde{\gamma} & \downarrow p \\ I & \xrightarrow{\gamma} & S^1 \end{array}$$

By commutativity of the above diagram, we have that $p \circ \tilde{\gamma}(1) = \gamma(1) = \gamma(0) = 1$, thus $\tilde{\gamma}(1) \in p^{-1}(1)$. Since $p^{-1}(1) = \mathbb{Z} \subseteq \mathbb{R}$, this implies that $\tilde{\gamma}(1)$ is some integer n .

There is another path in \mathbb{R} from 0 to n : it is the lift $\tilde{\omega}_n : I \rightarrow \mathbb{R}$. We have a homotopy from $\tilde{\gamma}$ to $\tilde{\omega}_n$:

$$H : I \times I \rightarrow \mathbb{R}, \quad H(s, t) = (1 - t)\tilde{\gamma}(s) + t \cdot \tilde{\omega}_n(s).$$

Now we can just compose with p , getting a map $p \circ H : I \times I \rightarrow \mathbb{R} \rightarrow S^1$. By construction, this map exhibits a homotopy between γ and ω_n . Hence $[\omega_n] = [\gamma]$, so ϕ is surjective.

Now, suppose that $\gamma : I \rightarrow S^1$ is some path such that $\gamma \simeq \omega_n$ and $\gamma \simeq \omega_m$. Homotopy equivalence is transitive, so there is a homotopy

$$H : I \times I \rightarrow S^1$$

from ω_n to ω_m . By **Homotopy path lifting**, there is a unique lift $\tilde{H} : I \times I \rightarrow \mathbb{R}$ such that $\tilde{H}(0, t) = 0$.

$$\begin{array}{ccc} & \mathbb{R} & \\ & \nearrow \tilde{H} & \downarrow p \\ I \times I & \xrightarrow{H} & S^1 \end{array}$$

By uniqueness of path lifting, since $\tilde{H}(s, 0)$ is a lift of ω_n which starts at 0 and ends at n , we must have that $\tilde{H}(s, 0) = \tilde{\omega}_n(s)$. Similarly, $\tilde{H}(s, 1) = \tilde{\omega}_m(s)$. Since \tilde{H} is a path homotopy, we must have that $\tilde{H}(1, t)$ is a fixed point $x \in \mathbb{R}$. When $t = 0$, we see that $\tilde{H}(1, 0) = \tilde{\omega}_n(1) = n$. When $t = 1$, we see that $\tilde{H}(1, 1) = \tilde{\omega}_m(1) = m$. Therefore, we must have that $n = m$, hence ϕ is injective, finishing the proof.

Lecture 6.

Alright! We have our first nontrivial fundamental group computation. How far can we milk it? In other words, are there other spaces out there whose fundamental group we can compute with our knowledge?

To really answer this question, we should develop a few more tools for working with the fundamental group. Let (X, x_0) and (Y, y_0) be based spaces, and consider their product $(X \times Y, (x_0, y_0))$. There are continuous projection maps

$$\begin{aligned} p_X : (X \times Y, (x_0, y_0)) &\rightarrow (X, x_0), & p_X(x, y) &= x, \\ p_Y : (X \times Y, (x_0, y_0)) &\rightarrow (Y, y_0), & p_Y(x, y) &= y. \end{aligned}$$

Recall from our last homework that continuous maps of based spaces induce group homomorphisms between fundamental groups. Thus, the projection maps induce group homomorphisms

$$\begin{aligned} (p_X)_* : \pi_1(X \times Y, (x_0, y_0)) &\rightarrow \pi_1(X, x_0), \\ (p_Y)_* : \pi_1(X \times Y, (x_0, y_0)) &\rightarrow \pi_1(Y, y_0). \end{aligned}$$

Each of these induced maps just takes a loop in $X \times Y$ and postcomposes with the projection map. The point of the following proposition is that these projection maps let us reconstruct the fundamental group of the product space for the fundamental groups of its factors.

Proposition 2.14. *The group homomorphism*

$$P = ((p_X)_*, (p_Y)_*) : \pi_1(X \times Y, (x_0, y_0)) \rightarrow \pi_1(X, x_0) \times \pi_1(Y, y_0)$$

defined on loops $\gamma : I \rightarrow X \times Y$ by

$$P([\gamma]) = ((p_X)_*([\gamma]), (p_Y)_*([\gamma])) \in \pi_1(X, x_0) \times \pi_1(Y, y_0)$$

is an isomorphism.

Proof. First, we show surjectivity. For any $[\varphi] \in \pi_1(X, x_0)$ and $[\psi] \in \pi_1(Y, y_0)$, define the loop $f : I \rightarrow X \times Y$ be the loop given by

$$f(t) = (\varphi(t), \psi(t)).$$

Notice that by construction, $p_X \circ f = \varphi$ and $p_Y \circ f = \psi$. Then we have

$$P([f]) = ((p_X)_*([f]), (p_Y)_*([f])) = ([p_X \circ f], [p_Y \circ f]) = ([\varphi], [\psi]).$$

This establishes surjectivity.

We next show that P is injective. Suppose that $[f] \in \pi_1(X \times Y, (x_0, y_0))$ is a loop such that $P([f]) = ([c_{x_0}], [c_{y_0}])$ (remember that the identity element of the fundamental group is the constant loop at the basepoint, so the identity element of the product is the ordered pair consisting of the constant paths at the respective basepoints). By definition, we have

$$p_X \circ f \simeq c_{x_0}, \quad p_Y \circ f \simeq c_{y_0}.$$

Let $H_1 : I \times I \rightarrow X$ be the first homotopy and $H_2 : I \times I \rightarrow Y$ the second. We can just “do these homotopies in each coordinate” to show that $[f] = [c_{(x_0, y_0)}]$. Let $H : I \times I \rightarrow X \times Y$ be defined by

$$H(s, t) = (H_1(s, t), H_2(s, t)).$$

Observe:

$$H(s, 0) = (H_1(s, 0), H_2(s, 0)) = (p_X \circ f(s), p_Y \circ f(s)) = f(s),$$

and

$$H(s, 1) = (H_1(s, 1), H_2(s, 1)) = (c_{x_0}(s), c_{y_0}(s)) = (x_0, y_0) = c_{(x_0, y_0)}(s).$$

Thus, H is a homotopy from f to $c_{(x_0, y_0)}$, so P must be injective. Therefore P is an isomorphism. \square

Exercise 2.15. This generalizes to finite products of any length! Namely, the map

$$P = ((p_{X_i})_*)_{i=1}^n : \pi_1 \left(\prod_{i=1}^n X_i, (x_i)_{i=1}^n \right) \rightarrow \prod_{i=1}^n \pi_1(X_i, x_i)$$

is an isomorphism of groups.

This tells us some cool stuff. For example:

- The torus $T = S^1 \times S^1$ has fundamental group

$$\pi_1(T) = \pi_1(S^1 \times S^1) = \pi_1(S^1) \times \pi_1(S^1) = \mathbb{Z} \times \mathbb{Z}.$$

You can imagine the two distinct \mathbb{Z} 's as “going around the holes” of T in different ways. One can travel around the circumference of the torus, and one can also travel along the circle going inwards towards the center. These are the two generators for $\pi_1(T)$.

- Similarly, the n -torus $S^1 \times \cdots \times S^1$ has fundamental group $\mathbb{Z} \times \cdots \times \mathbb{Z}$.
- We have seen that the fundamental group of \mathbb{R} is trivial, as is \mathbb{R}^n for any n . In particular, this implies that the $\pi_1(S^1 \times \mathbb{R}) \cong \pi_1(S^1 \times \mathbb{R}^n) = 0$.

We showed on the homework that $M \simeq S^1$, where M denotes the Möbius strip. In fact, the fundamental group respects this homotopy equivalence!

Proposition 2.16. *Let $f : X \rightarrow Y$ be a homotopy equivalence. Then for any $x_0 \in X$, the induced map*

$$f_* : \pi_1(X, x_0) \rightarrow \pi_1(Y, f(x_0))$$

is an isomorphism.

As a result, we get two more calculations:

- If $X \simeq S^1$, then $\pi_1(S^1) \cong \mathbb{Z}$. So, spaces like the annulus or the Möbius strip have fundamental groups given by \mathbb{Z} .
- If $X \simeq *$, then $\pi_1(X) = 0$.

Proof. Since $f : X \rightarrow Y$ is a homotopy equivalence, there is a homotopy inverse $g : Y \rightarrow X$, i.e. we have $f \circ g \simeq \text{id}_Y$ and $g \circ f \simeq \text{id}_X$. To show that f_* is an isomorphism, we would like to say that, well, g is a homotopy inverse, so g_* ought to be a group inverse as well! That is, one might guess that

$$f_* \circ g_* = \text{id}_{\pi_1(Y, y_0)}, \quad g_* \circ f_* = \text{id}_{\pi_1(X, x_0)}.$$

However, it is not *quite* this simple. Implicitly, we are assuming above that if $x_0 \in X$ is a chosen basepoint, that $g \circ f(x_0) = x_0$. However, this need not be the case at all. In particular, the domain and codomain of

$$g_* \circ f_* : \pi_1(X, x_0) \rightarrow \pi_1(Y, f(x_0)) \rightarrow \pi_1(X, g(f(x_0)))$$

need not be the same group. **HOWEVER...** we can surmount this obstacle.

Since $g \circ f \simeq \text{id}_X$, there is a homotopy

$$H : X \times I \rightarrow X$$

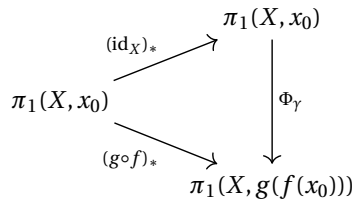
where $H(x, 0) = g \circ f(x)$ and $H(x, 1) = x$. In fact, (even without any assumption on path-connectedness of X !) this allows us to create a path from $g(f(x_0))$ to x_0 : let $\gamma : I \rightarrow X$ be defined by

$$\gamma(t) = H(x_0, t).$$

Then $\gamma(0) = H(x_0, 0) = g \circ f(x_0)$ and $\gamma(1) = H(x_0, 1) = x_0$. Recall from the proof that the fundamental group of a path-connected space is independent of choice of basepoint that the map

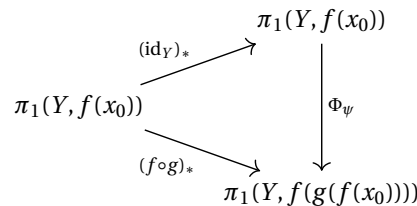
$$\Phi_\gamma : \pi_1(X, x_0) \rightarrow \pi_1(X, g(f(x_0))), \quad \Phi_\gamma([\psi]) = [\gamma] \cdot [\psi] \cdot [\gamma^{\text{rev}}]$$

is an isomorphism of groups. It is an exercise in symbol pushing (a good one, if you want to try it!) to show that Φ_γ fits into a commutative diagram of the form



By the first homework assignment, we saw that $(\text{id}_X)_* = \text{id}_{\pi_1(X, x_0)}$. In particular, it is an isomorphism. We also saw that $(g \circ f)_* = g_* \circ f_*$. Since Φ_γ is also an isomorphism, commutativity implies that $g_* \circ f_*$ is an isomorphism, thus f_* is injective (and g_* is surjective).

Alternatively, we can use the homotopy between $f \circ g \simeq \text{id}_Y$ to get a path $\psi : I \rightarrow Y$ from $f(x_0)$ to $f(g(f(x_0)))$ (this is annoying and cumbersome to write but it is what it is) and form the associated map of fundamental groups Φ_ψ . Again, this fits into a commutative diagram of the form



Again, we have $(\text{id}_Y)_* = \text{id}_{\pi_1(Y, f(x_0))}$ and Φ_ψ are isomorphisms, so $(g \circ f)_* = g_* \circ f_*$ must also be. Therefore f_* is surjective (and g_* is injective), so f_* is an isomorphism. \square

Lecture 7.

There are many more fun things to do with the fundamental group. Some of these things are on Homework 2. One of them is the next theorem, which is a real cornerstone in “using algebra to solve topological problems”. Recall that $\overline{\mathbb{D}^2} \subseteq \mathbb{R}^2$ denotes the closed unit disk.

Theorem 2.17 (Brouwer Fixed Point Theorem). *Let $f : \overline{\mathbb{D}^2} \rightarrow \overline{\mathbb{D}^2}$ be any continuous map. Then there is some point $x \in \overline{\mathbb{D}^2}$ such that $f(x) = x$.*

Proof. For sake of contradiction, suppose that $f(x) \neq x$ for all points $x \in \overline{\mathbb{D}^2}$. Define a function $r : \overline{\mathbb{D}^2} \rightarrow S^1$ by sending $x \in \overline{\mathbb{D}^2}$ to the point on S^1 at the end of the ray in \mathbb{R}^2 which starts at $f(x)$ and passes through x . Note that this is well-defined as two distinct points specify a line, and as $f(x) \neq x$, this ray always contains two distinct points. Notice also that if $y \in S^1 \subseteq \overline{\mathbb{D}^2}$ lies on the boundary, then this ray intersects S^1 at exactly x . In other words, $r(y) = y$. Moreover, restricting the domain of r to S^1 gives the map

$$r|_{S^1} : S^1 \rightarrow S^1,$$

and by our previous argument, we have that $r|_{S^1} = \text{id}_{S^1}$.

Consider the composition of continuous functions

$$S^1 \xrightarrow{i} \overline{\mathbb{D}^2} \xrightarrow{r} S^1.$$

This induces group homomorphisms on the corresponding fundamental groups

$$\pi_1(S^1) \xrightarrow{i_*} \pi_1(\overline{\mathbb{D}^2}) \xrightarrow{r_*} \pi_1(S^1).$$

Notice that the composition $r \circ i$ is the same as $r|_{S^1}$, which we also know is the same as id_{S^1} . Since $(\text{id}_{S^1})_* \cong \text{id}_{\pi_1(S^1)}$, the composition $r_* \circ i_*$ is equal to the identity map on $\pi_1(S^1) \cong \mathbb{Z}$. However, since $\overline{\mathbb{D}^2} \simeq *$, we have that $\pi_1(\overline{\mathbb{D}^2}) = 0$. This means we can rewrite the diagram of induced maps on fundamental groups as

$$\mathbb{Z} \xrightarrow{i_*} 0 \xrightarrow{r_*} \mathbb{Z}.$$

From this perspective, we must have that $r_* \circ i_*$ is the 0 map. This contradicts our previous finding, so there must be some point where $f(x) = x$. \square

This ends (for now) the discussion on the fundamental group. We now move into our next topic for the course: category theory.

3. CATEGORY THEORY

Lecture 8.

We have seen that there are nice invariants of spaces known as homotopy groups, and have gotten our hands dirty a little bit with the first of these invariants, i.e. the fundamental group. This process takes topology and assigns to it some algebra, and it does so in a way that “preserves structure”. To be precise, to any based space (X, x_0) we assigned a group $\pi_1(X, x_0)$, and to any continuous map of based spaces $f : (X, x_0) \rightarrow (Y, y_0)$ we assigned a group homomorphism $f_* : \pi_1(X, x_0) \rightarrow \pi_1(Y, y_0)$. Moreover, this procedure respects function composition and sends the identity map of spaces to the identity map of fundamental groups.

One of the goals of category theory is to generalize this relationship. In doing so, we create a very general, theoretical area of math that is widely applicable, serving as a language to interpret and demystify various phenomena which makes you say “huh, that is kinda similar to this other thing I saw one time...”

3.1. **Categories.** A *category* \mathcal{C} consists of the following data:

- A class of *objects*, which we may denote by $\text{ob}(\mathcal{C})$;
- For any two objects $X, Y \in \mathcal{C}$, a set of *morphisms* or *maps* $\text{Hom}_{\mathcal{C}}(X, Y)$, i.e. $f \in \text{Hom}_{\mathcal{C}}(X, Y)$ may be represented by some arrow $f : X \rightarrow Y$;
- A *composition* operation, meaning for any objects $X, Y, Z \in \text{ob}(\mathcal{C})$, there is a function of sets

$$\circ : \text{Hom}_{\mathcal{C}}(Y, Z) \times \text{Hom}_{\mathcal{C}}(X, Y) \rightarrow \text{Hom}_{\mathcal{C}}(X, Z)$$

which represents composition: if $f \in \text{Hom}_{\mathcal{C}}(X, Y)$ and $g \in \text{Hom}_{\mathcal{C}}(Y, Z)$, then $g \circ f \in \text{Hom}_{\mathcal{C}}(X, Z)$ is the map you would expect: $X \xrightarrow{f} Y \xrightarrow{g} Z$. Composition satisfies two rules:

- (*Associativity*) Whenever this expression makes sense, we have

$$(h \circ g) \circ f = h \circ (g \circ f).$$

- (*Identity*) For all $X \in \text{ob}(\mathcal{C})$, there is an identity map $\text{id}_X \in \text{Hom}_{\mathcal{C}}(X, X)$ such that for any morphism $f \in \text{Hom}_{\mathcal{C}}(X, Y)$, we have

$$f \circ \text{id}_X = \text{id}_Y \circ f = f.$$

We say that a morphism $f \in \text{Hom}_{\mathcal{C}}(X, Y)$ is an *isomorphism* if there exists another morphism $g \in \text{Hom}_{\mathcal{C}}(Y, X)$ such that

$$f \circ g = \text{id}_Y, \quad g \circ f = \text{id}_X.$$

You should think of the objects of a category as a collection of “types of things” one does mathematics with, and the morphisms as functions which preserve the inherent structure that these objects have. Here are some familiar categories.

Example 3.1.

- The collection of all sets and all set functions defines the category Set . The isomorphisms in this category are bijections.
- The collection of all topological spaces and all continuous functions defines the category $\mathcal{T}\text{op}$. The isomorphisms in this category are homeomorphisms.
- We also have a category $\text{h}\mathcal{T}\text{op}$ with the same objects, but with morphisms given by homotopy classes of continuous functions. The isomorphisms in this category are homotopy equivalences.
- The collection of all based topological spaces and all basepoint preserving continuous functions defines the category $\mathcal{T}\text{op}_*$. The isomorphisms are based homeomorphisms. Similarly to above, we also have a category $\text{h}\mathcal{T}\text{op}_*$. The isomorphisms are based path-homotopy equivalences.
- The collection of all vector spaces over a field k and all linear transformations defines the category Vect_k . The isomorphisms are vector space isomorphisms.
- The collection of all R -modules over a commutative ring R with R -linear maps defines the category $\text{Mod}(R)$. The isomorphisms are module isomorphisms.
- The collection of all groups and group homomorphisms defines the category $\mathcal{G}\text{rp}$. The isomorphisms are group isomorphisms.
- The collection of all abelian groups and group homomorphism defines the category $\mathcal{A}\text{b}$. The isomorphisms are group isomorphisms.

However, the definition of a category is exceptionally general. While our first intuition for a category produces the ones listed above, there are many, many more examples. Here are some more exotic categories.

Example 3.2.

- Let (P, \leq) be a poset (so that \leq is a reflexive, antisymmetric, transitive binary relation). We may regard P as a category, which we will denote P_{\leq} , by letting every point $x \in P$ be an object $x \in \text{ob}(P_{\leq})$, and for every relation $x \leq y$ in P , assigning a unique morphism $x \rightarrow y$ in P_{\leq} . Since $x \leq x$, we have a unique morphism $x \rightarrow x$ (the identity!). Can you see how to get the other requirements to be a category from the poset relations?
- Let k be a field. There is a category $\mathcal{M}\text{at}_k$ whose objects are nonnegative integers $n \in \mathbb{N}$ and where a morphism $n \rightarrow m$ is represented by an $m \times n$ -matrix with entries in k . Composition is given by matrix multiplication.
- If \mathcal{C} is any category, then its *opposite category* \mathcal{C}^{op} has the same objects as \mathcal{C} , but for every morphism $f : x \rightarrow y$ in \mathcal{C} , we have a morphism $f^{\text{op}} : y \rightarrow x$ in \mathcal{C}^{op} .
- Let G be a group. Then we can construct a category, sometimes denoted BG or even just G , with only one object $*$ and where $\text{Hom}_{BG}(*, *) = G$. How does composition work? Well, we know how to multiply elements in a group, right?
- There is a category with two non-isomorphic objects between them and no morphisms between these objects. Here is a way to represent this category, where we suppress the isomorphisms:

$$\bullet \bullet$$

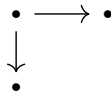
There is a variant of this category where there is a single morphism between our objects, which we can represent as

$$\bullet \rightarrow \bullet$$

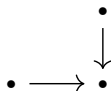
Or, say we had two distinct morphisms between our objects, which can be represented as



Or how about a category with three objects, and two morphisms that fit into the following diagram:



Or how about a category with three objects, and two morphisms going the other way?



Exercise 3.3. What are the isomorphisms in these funky categories?

The 4th example fits into a class of categories called *groupoids*. A category is a groupoid if every morphism is an isomorphism. Another example of a groupoid which we will see in Homework 2 is called the *fundamental groupoid*. If X is a topological space, then the fundamental groupoid of X , denoted $\Pi_1(X)$, is the category where:

- The objects of $\Pi_1(X)$ are the points of X , and
- For any two points $x, y \in X$, regarded as objects in $\Pi_1(X)$, a morphism $f \in \text{Hom}_{\Pi_1(X)}(x, y)$ is given by a homotopy class of paths.

We will soon see how this category captures the data of all of the different fundamental groups of X for different choices of basepoints.

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