

Math 619 Notes

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Contents

1 A preview of unstable vs stable homotopy theory

Unstable homotopy theory is the study of spaces up to homotopy, whereas stable homotopy is the study of spectra, which can be viewed as stable version of spaces, or from a different perspective, as a generalization of abelian groups. We will start with constructing the category of spaces and its homotopy category and work our way up to the construction the *the stable homotopy category*.

1.1 From spaces to spectra

The basic construction that we stabilize with respect to is the suspension functor Σ , which for a based space X is defined as $\Sigma X = X \wedge S^1$. Recall that for based spaces (X, x_0) and (Y, y_0) , the smash product is defined as

$$X \wedge Y := \frac{X \times Y}{(\{x_0\} \times Y) \cup (X \times \{y_0\})}.$$

Example 1.1. There is a homeomorphism $S^1 \wedge S^1 \cong S^2$.

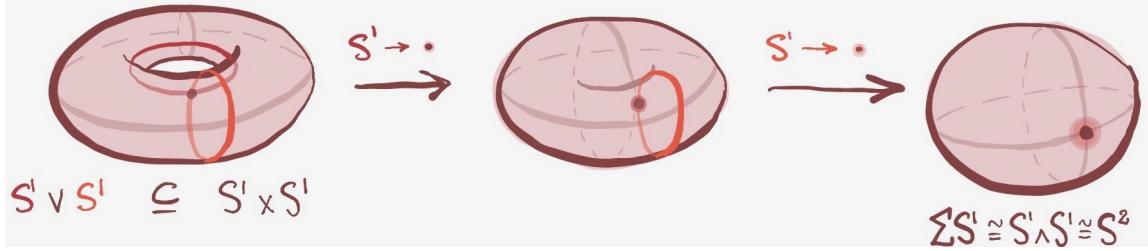


Figure 1: The homeomorphism $S^1 \wedge S^1 \cong S^2$.

In general, we have a similar homeomorphism

$$S^n \wedge S^m \cong S^{n+m}.$$

Let Ω be the loop functor, which for a based space X is defined as $\Omega X := \text{Map}_*(S^1, X)$, i.e., the space of loops in X based at the basepoint of X . There is an adjunction $\Sigma \dashv \Omega$, which means that we have a natural homeomorphism

$$\text{Map}_*(\Sigma X, Y) \cong \text{Map}_*(X, \Omega Y),$$

where this homeomorphism holds in our “convenient” category of spaces. Alternatively this is the data of a unit $X \rightarrow \Omega \Sigma X$ and a counit $\Sigma \Omega X \rightarrow X$ satisfying certain triangle identities. From this adjunction, we will end up seeing that the set of homotopy classes of based maps are isomorphic:

$$[\Sigma X, Y]_* \cong [X, \Omega Y]_*.$$

Higher homotopy groups of a space based space X are defined as homotopy classes of maps from higher dimensional spheres $\pi_n(X) = [S^n, X]_*$. The theorem that forms the bridge from unstable

to stable homotopy theory is the *Freudenthal suspension theorem*. Before stating it, we need a preliminary definition.

Definition 1.2. X is n -connected if $\pi_i(X) = 0$ for all $i \leq n$. For example, 0-connected means path connected and 1-connected means simply connected.

We may also define a suspension map on homotopy groups

$$\begin{aligned}\Sigma : \pi_q(X) &\rightarrow \pi_{q+1}(\Sigma X) \\ f &\mapsto [f \wedge \text{id} : S^{q+1} = S^q \wedge S^1 \rightarrow X \wedge S^1 = \Sigma X].\end{aligned}$$

Theorem 1.3. (*Freudenthal suspension theorem*) Assume that X is a based space which is n -connected. Then the morphism $\Sigma : \pi_q(X) \rightarrow \pi_{q+1}(\Sigma X)$ is:

- a bijection for $q \leq 2n$
- a surjection for $q = 2n + 1$.

By Freudenthal, $\pi_{q+n}(\Sigma^n X)$ stabilizes as n increases. This stable value is an interesting invariant on the space X .

Definition 1.4. The q th stable homotopy group of a space X is defined to be

$$\pi_q^s(X) := \underset{n}{\text{colim}} \pi_{q+n}(\Sigma^n X).$$

We observe that if X is $(n - 1)$ -connected, then for $q < n - 1$, the maps in the colimit system are isomorphisms. Thus we have that $\pi_q^s(X) = \pi_{q+n}(\Sigma^n X)$ for $q < n - 1$.

Remark 1.5. The computations of stable homotopy groups of spheres $\pi_q^s(S^0)$ is one of the deepest problems in algebraic topology. We will observe that these groups are deeply related to many questions throughout geometry and algebra as well.

We can take the idea of stabilizing a space that we have seen, and make the following definition of a *spectrum*, a stable analogue of a space.

Definition 1.6. A (pre)spectrum X is a sequence of based spaces X_0, X_1, \dots equipped with structure maps

$$\sigma_i : \Sigma X_i \rightarrow X_{i+1}$$

for each i .

Example 1.7. There is a *sphere spectrum*, denoted \mathbb{S} , whose n th space is the n -sphere S^n . The structure maps are the homeomorphisms $S^1 \wedge S^n \xrightarrow{\sim} S^{n+1}$ given by ??.

Example 1.8. Given any based space X , we denote by $\Sigma^\infty X$ its *suspension spectrum*, whose n th space is $\Sigma^n X$, and whose structure maps are the obvious homeomorphisms $\Sigma \Sigma^n X \xrightarrow{\sim} \Sigma^{n+1} X$. As an example, we have that $\mathbb{S} = \Sigma^\infty S^0$.

Definition 1.9. Given a spectrum X , we may define the n th stable homotopy group of X as

$$\pi_n(X) = \operatorname{colim}_k \left(\cdots \rightarrow \pi_{n+k}(X_k) \rightarrow \pi_{n+k+1}(\Sigma X_k) \xrightarrow{\sigma_{k,*}} \cdots \right)$$

Exercise 1.10. If X is a based space, then its q th stable homotopy group is the q th homotopy group of its suspension spectrum.

The collection of spectra form a category.

Definition 1.11. A *morphism of spectra* $X \rightarrow Y$ is a collection of maps $f_i : X_i \rightarrow Y_i$ at each level, which commute with the structure maps:

$$\begin{array}{ccc} \Sigma X_i & \xrightarrow{\Sigma f_i} & \Sigma Y_i \\ \sigma_i \downarrow & & \downarrow \sigma_i \\ X_{i+1} & \xrightarrow{f_{i+1}} & Y_{i+1}. \end{array}$$

Knowing what a weak homotopy equivalence of topological spaces is, we might want to define a notion of having a weak homotopy equivalence of spectra. One naive notion would be to define an equivalence to be a levelwise equivalence (i.e. $f : X \rightarrow Y$ is an equivalence if $f_i : X_i \rightarrow Y_i$ is a weak homotopy equivalence for each i). A better notion is to ask for a *stable equivalence*.

Definition 1.12. A *stable equivalence* of spectra is a morphism $f : X \rightarrow Y$ so that the induced map on homotopy groups

$$(f_q)_* : \pi_q(X) \xrightarrow{\sim} \pi_q(Y)$$

is an isomorphism for each q .

We may also define a category HoSp which is the localization of the category of spectra at the stable equivalences. That is, a functor $\text{Sp} \rightarrow \text{HoSp}$ which turns stable equivalences into isomorphisms, and is initial among functors with this property — that is, if there is another functor $\text{Sp} \rightarrow \mathcal{C}$ which sends stable equivalences to isomorphisms, we get a unique factorization

$$\begin{array}{ccc} \text{Sp} & \longrightarrow & \text{HoSp} \\ & \searrow & \downarrow \\ & & \mathcal{C}. \end{array}$$

However HoSp is a difficult category to work in, since it does not have many limits or colimits. A survey of the history of stable homotopy theory is given by [?]. For a great introduction to spectra and associated constructions, see [?], where you can find the following diagram relating different constructions that describe the passage between spaces and spectra, and abelian groups and spectra.

$$\begin{array}{ccccccc} \text{CW} & \xrightarrow{\text{disjoint basept.}} & \text{CW}_* & \xrightarrow{\Sigma^\infty} & \text{Sp} & \xleftarrow{H-} & \text{Ab} \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \text{0th component} \\ \text{Ho}(\text{CW}) & \longrightarrow & \text{Ho}(\text{CW}_*) & \longrightarrow & \text{Ho}(\text{Sp}) & \xrightarrow{\pi_*} & \text{Ab}^{\mathbb{Z}_{\geq 0}} \end{array}$$

For every abelian group G , there is an *Eilenberg-Maclane spectrum* HG which is described up to homotopy by the property that $\pi_0(HG) = G$ and $\pi_i(HG) = 0$ for $i \neq 0$, where $(HG)_n = K(G, n)$ for each n . We will construct this spectrum later on in the class.

1.2 Why should we care about spectra?

There is an amazing theorem called *Brown representability* that states that every cohomology theory $E^* : \text{HoCW} \rightarrow \text{Ab}^{\mathbb{Z}_{\geq 0}}$, satisfying certain axioms, is represented by a spectrum E , that is, $E^n(X) \cong [X, E_n]$ and E is unique up to isomorphism in HoSp . Equivalently, any spectrum yields a cohomology theory. Thus we can study generalized cohomology theories by directly studying spectra.

Here are some questions and applications where spectra are key.

Example 1.13. The enumeration of differentiable structures on spheres S^n for $n \geq 5$ is reduced to the computation of the stable homotopy groups of spheres.

Example 1.14. One can impose an equivalence relation on closed manifolds called *cobordism*.

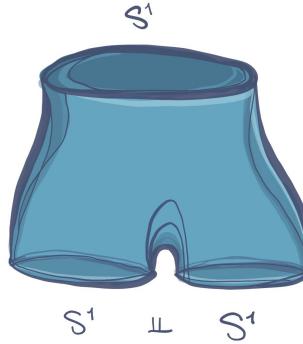


Figure 2: A cobordism from S^1 to $S^1 \amalg S^1$.

The classification question of closed manifolds up to cobordism is a central problem in differential topology. Amazingly, it turns out that this problem can be translated into stable homotopy theory. The groups Ω_n of closed n -manifolds up to cobordism was shown by Thom to be isomorphic to the homotopy groups homotopy groups of a spectrum MO .

Example 1.15. Consider the question: *For which n is \mathbb{R}^n a division algebra?* Of course, we know four examples, $\mathbb{R}, \mathbb{C} = \mathbb{R}^2, \mathbb{H} = \mathbb{R}^4, \mathbb{O} = \mathbb{R}^8$, are there any others? This is also equivalent to asking when S^{n-1} is an H -space, i.e., it has a continuous multiplication map with a two-sided identity element. This question is also known as *the Hopf invariant one problem* because it is also equivalent to the existence of a Hopf invariant one map $S^{2n-1} \rightarrow S^n$. This question was solved by Adams, initially in a 100 page paper, where he introduced the Adams spectral sequence for $\pi_q^s(S^0)$. He later gave a much shorter solution using K -theory. Stable homotopy theory is key in both solutions.

Example 1.16. Consider the question: *How many linearly independent everywhere nonzero vector fields can there be on S^{n-1} ?* This question was answered by Adams using K -theory, an extraordinary cohomology theory. The answer is that S^{n-1} admits exactly $\rho(n) - 1$ linearly independent everywhere nonzero vector fields, where $\rho(n)$ is the Radon-Hurwitz number equal to $2^c + 8d$, where $n = (2a+1)2^b$ and $b = c + 4d$ with $0 \leq c < 4$.

Example 1.17. A very old question in differential topology dating back to the 1960s was: *For which n does there exist a stably framed n -manifold with the Kervaire invariant one?* This is known as the *Kervaire invariant one problem*. The Kervaire invariant of a smooth stably framed manifold is the so-called Arf-invariant of an associated quadratic form $H^{\frac{n}{2}}(M, \mathbb{Z}/2) \rightarrow \mathbb{Z}/2$. The answer to the Kervaire invariant 1 problem is yes in dimensions $n = 2, 6, 14, 62$ and possibly 126, but it was ruled out in all other dimensions in 2009 by a recent breakthrough result of Hill, Hopkins and Ravenel [?]. This question can again be translated into the survival of certain elements in the Adams spectral sequence for the stable homotopy groups of spheres, and it was further translated by the authors into a question in equivariant stable homotopy theory and solved in that setting.

1.3 Some references

The notes for this course will mostly be based on [?], [?], and we often follow [Bert Guillou's course notes](#). These will be supplemented with many other resources along the way, which we will specify and reference in each subsection accordingly.

2 The category of spaces

We start with some recollections about basic category theory and we construct the “convenient category of topological spaces” which modern algebraic topologists work in.

2.1 Category theory review

We refer the reader to the following excellent sources for the basics of category theory. The sets of notes [?], [?] and [?] are great introductions and so are the textbooks [?] and [?]. The standard reference for category, which was the first book on the subject is still [?]. We skip the definition of category but recall a list of standard examples of categories that you have certainly encountered before.

Also, here are some examples of functors between some of these categories, which we have probably encountered before:

- the forgetful functor $U : \mathbf{Grp} \rightarrow \mathbf{Set}$ which forgets the group structure
- the free functor $F : \mathbf{Set} \rightarrow \mathbf{Grp}$ which takes the free group on a set
- homology $H_i : \mathbf{Top}_* \rightarrow \mathbf{Grp}$
- homotopy groups $\pi_i : \mathbf{Top}_* \rightarrow \mathbf{Grp}$

Table 1: Examples of categories

Category	Objects	Morphisms
Set	sets	set functions
Grp	groups	group homomorphisms
Ab	abelian groups	group homomorphisms
Ring	rings	ring homomorphisms
Top	topological spaces	continuous maps
Top_*	based spaces	based continuous maps
Vect(k)	vector spaces over a field k	linear maps
1	single object	only identity arrow
2	two objects, denoted 0 and 1	single non-identity morphism $0 \rightarrow 1$.

- cohomology $H^i : \text{Top}^* \rightarrow \text{Grp}$, which is a *contravariant* functor.

Example 2.1. Suppose that G is a group. Then we may form a category G with one object, and whose morphism set is all of G . Composition is given by the group law. A functor $G \rightarrow \text{Set}$ is exactly the data of a G -set, that is, a set equipped with an action of G . Similarly, a functor $G \rightarrow \mathcal{C}$ is referred to as a G -object in \mathcal{C} .

Definition 2.2. For any category \mathcal{C} , we can define its *opposite category*, denoted \mathcal{C}^{op} , whose objects are the same as \mathcal{C} , but whose morphisms have the domain and codomain swapped, and whose composition is defined to mirror the composition in \mathcal{C} . That is, a morphism $x \xrightarrow{f} y$ in \mathcal{C} corresponds to a morphism $y \xrightarrow{f^{\text{op}}} x$, and we define $g^{\text{op}} \circ f^{\text{op}} := (f \circ g)^{\text{op}}$.

Note that for any category \mathcal{C} , we have that $(\mathcal{C}^{\text{op}})^{\text{op}}$ is just \mathcal{C} . The construction \mathcal{C}^{op} occurs frequently in mathematics. The opposite category \mathcal{C}^{op} can be very different than the category \mathcal{C} . Some interesting examples follow:

- the category of affine schemes is equivalent to Ring^{op}
- the opposite category of finite sets is equivalent to the category of finite Boolean algebras
- the category Top^{op} is, in some sense, equivalent to the category of frames (for a discussion of this, see [?])

Note on terminology: The classical notion of a contravariant functor from $\mathcal{C} \rightarrow \mathcal{D}$ can be thought of as a covariant functor $\mathcal{C}^{\text{op}} \rightarrow \mathcal{D}$, thus so long as we specify the domain category, we may often refer to a functor with the implicit assumption that it is covariant.

Definition 2.3. Let $F, G : \mathcal{C} \rightarrow \mathcal{D}$ be covariant functors. A *natural transformation* $\eta : F \Rightarrow G$ is a collection of morphisms $\eta_x : Fx \rightarrow Gx$ for each $x \in \mathcal{C}$, such that, for every $x \xrightarrow{f} y$ in \mathcal{C} , we have that the diagram commutes

$$\begin{array}{ccc} Fx & \xrightarrow{Ff} & Fy \\ \eta_x \downarrow & & \downarrow \eta_y \\ Gx & \xrightarrow{Gf} & Gy. \end{array}$$

Definition 2.4. A *natural isomorphism* is a natural transformation $\eta : F \Rightarrow G$ such that the components $\eta_c : Fc \xrightarrow{\cong} Gc$ is an isomorphism for each $c \in \mathcal{C}$.

For any two categories \mathcal{C} and \mathcal{D} , we can define the product category $\mathcal{C} \times \mathcal{D}$, with objects and morphisms given by pairs of objects and morphisms, and identities and composition defined componentwise.

Exercise 2.5. Show that the data of a natural transformation is the same as a functor $H : \mathcal{C} \times \mathbb{2} \rightarrow \mathcal{D}$, such that $H(-, 0) = F$ and $H(-, 1) = G$.

Example 2.6. Let $(-)^{**} : \text{Vect}(\mathbb{R}) \rightarrow \text{Vect}(\mathbb{R})$ denote the double dual functor. We have a natural transformation $\eta : \text{id}_{\text{Vect}(\mathbb{R})} \Rightarrow (-)^{**}$ whose components are the isomorphisms $\eta_V : V^{**} \rightarrow V$ given by $x \mapsto [\text{ev}_x : V^* \rightarrow \mathbb{R}]$. One may check that the corresponding diagram commutes, and gives a natural isomorphism.

Remark 2.7. For every V , there also exists an isomorphism $V \cong V^*$, however there is no natural isomorphism $\text{id} \Rightarrow (-)^*$.

Definition 2.8. We define $\mathcal{D}^\mathcal{C}$ or $\text{Fun}(\mathcal{C}, \mathcal{D})$ as the *functor category* whose objects are functors $\mathcal{C} \rightarrow \mathcal{D}$ and whose morphisms are natural transformations.

Let \mathcal{C} be a *locally small* category, meaning that $\text{Hom}_{\mathcal{C}}(a, b)$ is a set for each pair of objects in \mathcal{C} . For each $c \in \mathcal{C}$, we obtain functors

$$\begin{aligned}\text{Hom}_{\mathcal{C}}(c, -) &: \mathcal{C} \rightarrow \text{Set} \\ \text{Hom}_{\mathcal{C}}(-, c) &: \mathcal{C}^{\text{op}} \rightarrow \text{Set}\end{aligned}$$

Thomas: is this an okay convention though? I feel like in general, $\mathcal{D}^\mathcal{C}$ denotes \mathcal{D} -valued presheaves on \mathcal{C} , so functors $\mathcal{C}^{\text{op}} \rightarrow \mathcal{D}$

Functors of this form are called *representable*. The Yoneda lemma says that the set of natural transformations $\text{Hom}_{\mathcal{C}}(-, c) \Rightarrow F$ is in bijection with $F(c)$, naturally in c .

Lemma 2.9 (Yoneda Lemma, covariant version). Let $F : \mathcal{C} \rightarrow \text{Set}$. There is a bijection

$$\text{Hom}_{\text{Set}^\mathcal{C}}(\text{Hom}_{\mathcal{C}}(c, -), F) \cong F(c),$$

naturally in both c and F .

Exercise 2.10. Prove the Yoneda lemma.

Hint: There are two parts to this. First, define the required set isomorphism. Second, draw out the naturality squares, along maps $c \rightarrow c'$ and along natural transformations $F \Rightarrow F'$ and check that with the definition of the isomorphism you gave, these squares commute. A reference for the proof is for example [?, Lemma 2.5].

There is an equivalent contravariant version of the Yoneda lemma. Moreover, it turns out we can prove two objects in a category are isomorphic by showing that the representables are naturally isomorphic.

Lemma 2.11. Suppose that there is a natural isomorphism of functors

$$\eta : \text{Hom}_{\mathcal{C}}(c, -) \cong \text{Hom}_{\mathcal{C}}(d, -).$$

Then $c \cong d$ in \mathcal{C} .

Proof. We can show that $\eta_c(\text{id}_c): d \rightarrow c$ is an isomorphism. Since η_d is an isomorphism, there exists an $f: c \rightarrow d$ such that $\eta_d(f) = \text{id}_d$. Considering the naturality square

$$\begin{array}{ccc} \text{Hom}_{\mathcal{C}}(c, c) & \xrightarrow{\eta_c} & \text{Hom}_{\mathcal{C}}(d, c) \\ \circ f \downarrow & & \downarrow \circ f \\ \text{Hom}_{\mathcal{C}}(c, d) & \xrightarrow{\eta_d} & \text{Hom}(d, d) \end{array}$$

we can see that $f \circ \eta_c(\text{id}_c) \circ f = \text{id}_d$. Similarly considering the naturality square for $\eta_c(\text{id}_c): d \rightarrow c$ we can show that $\eta_c(\text{id}_c) \circ f = \text{id}_c$. \square

2.2 Adjoint pairs of functors

Let \mathbf{Cat} be the category of categories and functors. Note that in any category, there is a looser way that objects can be “the same” than equality: two objects C and D are defined to be isomorphic if there are morphisms $f: C \rightarrow D$ and $g: D \rightarrow C$ such that $fg = \text{id}$ and $gf = \text{id}$. In particular, in the category \mathbf{Cat} , two categories \mathcal{C} and \mathcal{D} are isomorphic if there are functors $F: \mathcal{C} \rightarrow \mathcal{D}$ and $G: \mathcal{D} \rightarrow \mathcal{C}$ such that $FG = \text{id}$ and $GF = \text{id}$. However, we have seen that there is a looser notion that we can use to compare functors than equality: we have defined a notion of isomorphic functors, which leads to the definition of *equivalence of categories*.

Definition 2.12. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is an *equivalence of categories* if there exists $G: \mathcal{D} \rightarrow \mathcal{C}$ such that $FG \cong \text{id}_{\mathcal{D}}$ and $GF \cong \text{id}_{\mathcal{C}}$ are natural isomorphisms of functors. We say that F is an *isomorphism of categories* if $FG = \text{id}_{\mathcal{D}}$ and $GF = \text{id}_{\mathcal{C}}$.

Recall that for a set function having an inverse is equivalent to being injective and surjective. An analogous result regarding equivalences of categories is the following.

Proposition 2.13. $F: \mathcal{C} \rightarrow \mathcal{D}$ is an equivalence of categories if and only if F is:

- *faithful*, meaning that $\text{Hom}_{\mathcal{C}}(c, c') \hookrightarrow \text{Hom}_{\mathcal{D}}(Fc, Fc')$ is injective for each c, c'
- *full*, meaning that $\text{Hom}_{\mathcal{C}}(c, c') \twoheadrightarrow \text{Hom}_{\mathcal{D}}(Fc, Fc')$ is surjective for each c, c'
- *essentially surjective on objects*, meaning for each $d \in \mathcal{D}$ there exists $c \in \mathcal{C}$ such that $F(c) \cong d$.

Exercise 2.14. Prove the proposition. *A reference for the proof is [?, Proposition 1].*

More generally we have a notion of having a map between functors, i.e., a natural transformation. We can ask for two categories to be related in an even weaker sense than the notion of equivalence we have defined by simply requiring that we have natural transformations between the two composites and identities, but without requiring that these are isomorphisms. We do impose a condition that ensures that the two natural transformations do interact nicely with each other.

Definition 2.15. Given a pair of functors $F: \mathcal{C} \leftrightarrows \mathcal{D}: G$, we say they are *adjoint* if there exist natural transformations $\eta: \text{id}_{\mathcal{C}} \Rightarrow GF$ (called the *unit*) and $\epsilon: FG \Rightarrow \text{id}_{\mathcal{D}}$ (called the *counit*) satisfying the triangle identities:

$$\begin{array}{ccc}
 F(a) & \xrightarrow{F\eta_a} & FGF(a) \\
 \swarrow & & \downarrow \epsilon_{F(a)} \\
 & & F(a)
 \end{array}
 \quad
 \begin{array}{ccc}
 G(b) & \xrightarrow{\eta_{G(b)}} & GFG(b) \\
 \searrow & & \downarrow G(\epsilon_b) \\
 & & G(b),
 \end{array}$$

for each $a \in \mathcal{C}, b \in \mathcal{D}$.

We will give three more definitions of an adjunction, which we claim are all equivalent to each other. We can define an adjunction in terms of just the unit or the counit together with a universal property.

Definition 2.16. Given a pair of functors $F: \mathcal{C} \leftrightarrows \mathcal{D}: G$, we say they are *adjoint* if there exists a natural transformations $\eta: \text{id}_{\mathcal{C}} \Rightarrow GF$ (called the *unit*) such that for any object C of \mathcal{C} and D of \mathcal{D} and any map $f: C \rightarrow G(D)$ there exists a unique map $g: F(C) \rightarrow D$ so that the following diagram commutes:

$$\begin{array}{ccc}
 C & \xrightarrow{\eta_C} & GF(C) \\
 \downarrow f & \swarrow Ug & \\
 U(D) & &
 \end{array}$$

Definition 2.17. (Dual definition specifying the counit instead of the unit.)

Lastly, we can give a definition in terms of a natural isomorphism of hom-sets when the categories \mathcal{C} and \mathcal{D} are both locally small so that $\text{Hom}_{\mathcal{D}}(F(a), b)$ and $\text{Hom}_{\mathcal{C}}(a, G(b))$ are sets. Oftentimes, the following is given as the definition of an adjunction.

Definition 2.18. Given a pair of functors $F: \mathcal{C} \leftrightarrows \mathcal{D}: G$, we say they are *adjoint* if, for each $a \in \mathcal{C}, b \in \mathcal{D}$, there exists an isomorphism

$$\text{Hom}_{\mathcal{D}}(F(a), b) \cong \text{Hom}_{\mathcal{C}}(a, G(b)),$$

which is natural in both a and b .

Exercise 2.19. Demonstrate the equivalence of these four definitions.

Hint: These equivalences of definitions can all be found in the nLab entry on adjunctions. Also, the proof of the equivalence of ?? and ?? can be found as [?, Theorem 2.2.5] or [?, Theorem 3.9]. The equivalence of ?? and ?? can be found in [?, Section 3] or [?, Theorem 2.3.6.], where the universal property of the unit is formulated in terms of initial objects. The argument using ?? instead of ?? should be exactly analogous.

Examples 2.20. Here are some examples of adjunctions:

- Fix an abelian group B . Then for any abelian groups A and C , we have a natural isomorphism of sets

$$\text{Hom}_{\mathbf{Ab}}(A \otimes B, C) \cong \text{Hom}_{\mathcal{C}}(A, \text{Hom}_{\mathbf{Ab}}(B, C)).$$

That is, the functors $- \otimes B$ and $\text{Hom}_{\mathbf{Ab}}(B, -)$ are adjoint.

- We have a free-forgetful adjunction $F : \mathbf{Set} \leftrightarrows \mathbf{Grp} : U$
- $(-)_{+} : \mathbf{Top} \leftrightarrows \mathbf{Top}_{*} : U$ is an adjunction. We see this since

$$\mathbf{Top}(X, UY) \cong \mathbf{Top}_{*}(X_{+}, Y).$$

Proposition 2.21. Adjoints compose.

Exercise 2.22. Let $F : \mathcal{C} \rightleftarrows \mathcal{D} : G$ be an adjunction. Then

1. F is fully faithful if and only if the unit $\eta : \text{id}_{\mathcal{C}} \rightarrow GF$ is a natural isomorphism.
2. G is fully faithful if and only if the counit $\epsilon : FG \rightarrow \text{id}_{\mathcal{D}}$ is a natural isomorphism.

Note that in ?? of equivalence of categories we only required that $GF \cong \text{id}$ and $FG \cong \text{id}$ were natural isomorphisms, but not necessarily that F and G are adjoint (namely, the triangle identities were not imposed). It turns out that every equivalence of categories can be modified to an adjoint equivalence by possibly changing the unit or counit. For a proof, see [?, Lemma 3.10].

2.3 A convenient category of spaces

For many years, algebraic topologists have been laboring under the handicap of not knowing in which category of spaces they should work. Our need is to be able to make a variety of constructions and to know that the results have good properties without the tedious spelling out at each step of lengthy hypotheses such as countably paracompact, normal, completely regular, first axiom of countability, metrizable, and so forth. It may be good research technique and an enjoyable exercise to analyse the precise circumstances for which an argument works; but if a developing theory is to be handy for research workers and attractive to students, then the simplicity of the fundamentals must be the goal.

[?]

The main references for this section are [?] and [?], and we refer the reader to those papers for all of the proofs of point set topology propositions. An excellent set of notes on this topic is also [?].

Recall that in \mathbf{Set} we have an adjunction between the product and the hom functor given by

$$\text{Hom}_{\mathbf{Set}}(A \times B, C) \cong \text{Hom}_{\mathbf{Set}}(A, \text{Hom}_{\mathbf{Set}}(B, C)).$$

Of course, the bijection follows from comparing cardinalities, but the point is that these bijections are natural, so they are compatible along morphisms in the category. We want a similar adjunction in the category of spaces.

Let Y^X or $\text{Map}(X, Y)$ denote the *mapping space* between two topological spaces, whose underlying set is the collection of continuous maps $X \rightarrow Y$, and which is equipped with the *compact-open topology*, generated by the subbasis

$$W_{K,U} = \{f : X \rightarrow Y : f(K) \subseteq U\},$$

indexed over $K \subseteq X$ compact and $U \subseteq Y$ open. We have a map

$$\text{Map}(X \times Y, Z) \rightarrow \text{Map}(X, \text{Map}(Y, Z)), \quad (1)$$

which is always a homeomorphism onto its image, but it is not always surjective. Thus $\text{Map}(Y, -)$ and $- \times Y$ are not adjoint. As we will see in the next section, any left adjoint in Top would need to preserve quotients, which is a type of colimit. However, by [?, Section 22, Example 7], The product of the quotient map $\mathbb{R} \rightarrow \mathbb{R}/\sim$, which identifies all of \mathbb{N} to a point, with \mathbb{Q} is not a quotient. Thus $- \times \mathbb{Q}$ cannot possibly be a left adjoint.

In order to turn Equation ?? into a homeomorphism, we define a class of spaces for which this is a homeomorphism.

Definition 2.23. A subspace $A \subseteq X$ is *k-closed in X* if, for all compact Hausdorff spaces K and continuous maps $K \xrightarrow{f} X$, we have that $f^{-1}(A)$ is closed in K .

Exercise 2.24. The collection of *k*-closed subsets of X forms a topology which contains the original topology on X (since closed implies *k*-closed).

Let kX denote the set X equipped with the *k*-closed topology. So kX has the same underlying set as X but its topology has more closed sets. We note that the identity map $kX \rightarrow X$ is continuous.

Definition 2.25. We say that a space X is *compactly generated (CG)* if the identity map $kX \rightarrow X$ is a homeomorphism. That is, if every *k*-closed set is closed in the original topology on X .

Some examples of CG spaces are metric spaces and all locally compact spaces, so in particular, CW complexes. The proofs that these spaces are CG can be found in [?, Propositions 1.6, 1.7]

Note that immediately from the definitions, if X is a compactly generated space, and Y is any space, then $f : X \rightarrow Y$ is continuous if and only if $f : X \rightarrow kY$ is continuous.

Upshot 2.26. For the functors $i : \text{CG} \leftrightarrows \text{Top} : k$, we have that

$$\text{Hom}_{\text{Top}}(iX, Y) \cong \text{Hom}_{\text{CG}}(X, kY),$$

so i is left adjoint to k .

Note 2.27. We have that $k^2X = kX$.

Note 2.28. The category CG is not closed under product and mapping spaces. So we must define

$$\begin{aligned} X \times_k Y &:= k(X \times Y) \\ \text{Map}_k(X, Y) &:= k\text{Map}(X, Y). \end{aligned}$$

Theorem 2.29. There exists a homeomorphism

$$\text{Map}(X \times_k Y, Z) \cong \text{Map}_k(X, \text{Map}_k(Y, Z)),$$

so CG is Cartesian closed. For a proof of this theorem, read [?, Proposition 2.11].

The category CG is good enough for most applications, but to make things a little better, we impose an additional separation axiom.

Definition 2.30. A topological space is *weak Hausdorff* if for all compact Hausdorff spaces K and every continuous map $f : K \rightarrow X$, we have that $f(K)$ is closed in X .

Exercise 2.31. Hausdorff implies weak Hausdorff.

Some examples of weak Hausdorff spaces are again CW complexes, metric spaces, etc. One of the reasons why we work with weak Hausdorff spaces as opposed to Hausdorff spaces is for example, for any closed inclusion $A \hookrightarrow X$ where X is weak Hausdorff, the quotient is also weak Hausdorff, though this would not necessarily be true in Hausdorff spaces. For example, the quotient of the C_2 -action on a pair of real lines \mathbb{R} which swaps the points between the lines outside of 0, and fixes 0 on both lines is the “line with two origins,” which is not Hausdorff. Another example is the quotient of the action of the additive subgroup \mathbb{Q} on \mathbb{R} , which is \mathbb{R}/\mathbb{Q} , which has the trivial topology so it is not Hausdorff.

Proposition 2.32. For a weak Hausdorff space X , any larger topology on X (i.e. a topology containing the original topology on X) will also be weak Hausdorff.

Another reason why we like weak Hausdorff spaces is because they interact nicely with compactly generated spaces. For example, by [?, Lemma 1.4. and Proposition 2.14]

- for X is a k -space, it is weak Hausdorff if and only if the diagonal $X \xrightarrow{\Delta} X \times_k X$ is closed,
- for X weak Hausdorff, it is a k -space if and only if the closed set C are precisely those for which $C \cap K$ is closed for every compact Hausdorff $K \subseteq X$.

Proposition 2.33. For $X \in \text{CG}$, we have that X / \sim is weak Hausdorff for some equivalence class on X if and only if \sim is closed (meaning the equivalence relation is closed as a subspace of $X \times X$).

For the proof of this, read [?, Corollary 2.21]. Now, by [?, Proposition 2.22], there is a smallest closed equivalence relation on a CG space X , so we can make the following definition.

Definition 2.34. For $X \in \text{CG}$, let $hX = X / \sim$, where \sim is the smallest closed equivalence relation on X . Let $j : \text{CGWH} \rightarrow \text{CG}$ denote the inclusion. Thus we have an adjunction

$$h : \text{CG} \leftrightarrows \text{CGWH} : j.$$

That is, $\text{Hom}_{\text{CG}}(X, jY) \cong \text{Hom}_{\text{CGWH}}(hX, Y)$.

Proposition 2.35. If $X, Y \in \text{CGWH}$ then $\text{Map}_k(X, Y)$ and $X \times_k Y$ are in CGWH . So CGWH is cartesian closed.

In other words, once in CG , passing to weak Hausdorff spaces, does not change products and mapping spaces. For the proofs, again see [?, Corollary 2.16 and Proposition 2.24].

2.4 Limits and colimits in categories

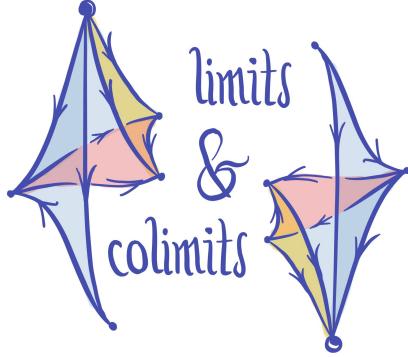


Figure 3: A limit cone and colimit cocone.

Definition 2.36. Let $F : I \rightarrow \mathcal{C}$ be a functor. We call this an *I-shaped diagram in \mathcal{C}* . The *colimit* of F , denoted $\text{colim } F$, is an object in \mathcal{C} together with a family of morphisms $F(X) \rightarrow \text{colim } F$ for each $X \in I$, such that

$$\begin{array}{ccc} F(X) & \xrightarrow{\quad\quad\quad} & F(Y) \\ & \searrow & \swarrow \\ & \text{colim } F & \end{array}$$

commutes for each $X \rightarrow Y$ in I , and moreover it satisfies a universal property so that for any other object $A \in \mathcal{C}$ with the above properties, we have that there exists a unique map $\text{colim } F \rightarrow A$ such that the diagram commutes

$$\begin{array}{ccc} F(X) & \xrightarrow{\quad\quad\quad} & F(Y) \\ & \searrow & \swarrow \\ & \text{colim } F & \\ & \downarrow & \downarrow \\ & A & \end{array}$$

for each $X \rightarrow Y$.

The *limit* of a diagram $F : I \rightarrow \mathcal{C}$ is dual to this definition, meaning that a limit is a colimit in the opposite category \mathcal{C}^{op} , i.e. the colimit of the composite functor $I \xrightarrow{F} \mathcal{C} \rightarrow \mathcal{C}^{\text{op}}$.

Proposition 2.37. Limits and colimits, when they exist, are unique up to isomorphism.

Exercise 2.38. Prove ??.

Before moving on to many examples, we state a proposition whose usefulness is hard to overestimate. It says that left adjoints preserve colimits and right adjoints preserve limits.

Proposition 2.39. (*LAPC and RAPL*¹) Let $F \dashv G$ be adjoint functors. Then F preserves colimits and G preserves limits.

Exercise 2.40. Prove ??.

Hint: Note that if you prove that right adjoint preserve limits, it will dually follow that left adjoints preserve colimits by considering opposite categories. Now, to prove RAPL, the simplest way to approach it is straight from the hom bijection definition of adjoints and the definition of limit. Namely, show that if L is a limit of a diagram in the domain category \mathcal{C} then GL satisfies the universal property of the limit in the target category \mathcal{D} . Another way would be to show that the proposition holds for representables and then go from there. Or, we using ??, which we will see in the next section, assuming limits exist, you can use that adjunction to prove that a right adjoint preserves limits.

Definition 2.41. Let $I = \bullet \bullet$ be the discrete category with two objects and no nontrivial morphisms. Then the limit over I is called the *product*, and the colimit over I is called the *coproduct*. Explicitly, where 0 and 1 denote the two objects in I , we have that

$$\lim_I F = F(0) \amalg F(1)$$

$$\operatorname{colim}_I F = F(0) \amalg F(1).$$

Examples 2.42. What follows are some examples of products and coproducts:

- In **Set**, a functor determines two sets $F(0) = A$ and $F(1) = B$, and their colimit $A \amalg B$ satisfies the universal property that, for any other set X equipped with morphisms $A \rightarrow X$ and $B \rightarrow X$, there is a unique map $A \amalg B \rightarrow X$ such that

$$\begin{array}{ccc} A & & B \\ & \searrow & \swarrow \\ & A \amalg B & \\ & \downarrow & \\ X & & \end{array}$$

commutes. This is exactly the coproduct of sets that we are familiar with. Dually, the limit $A \prod B$ satisfies the dual property that, for any X equipped with maps $X \rightarrow A$ and $X \rightarrow B$, there is a unique map such that

$$\begin{array}{ccc} & X & \\ & \downarrow & \\ A \prod B & & \\ & \swarrow & \searrow \\ A & & B \end{array}$$

Thus the product in **Set** is just the cartesian product.

¹Left adjoints preserve colimits and right adjoints preserve limits.

- In Top , the coproduct is disjoint union and the product is the product of spaces with the product topology.
- In Top_* , the coproduct is the wedge $A \vee B$, and the product is just the product of spaces $(A, a_0) \times (B, b_0)$ based at the point (a_0, b_0) .
- In Poset , the product $p \wedge q$ is the greatest lower bound, and the coproduct $p \vee q$ is the least upper bound (if they exist).
- In Grp , the product is the direct product, and the coproduct is the free product of groups.

Definition 2.43. If $I = \bullet \rightrightarrows \bullet$, then the colimit over I is called the *coequalizer* and the limit over I is called the *equalizer*.

Example 2.44. In Top , let $E \subseteq X \times X$ be an equivalence relation on X . Then

$$\text{colim} \left(E \xrightarrow{\pi_1} X \right) = X / \sim .$$

Definition 2.45. If $I = \bullet \leftarrow \bullet \rightarrow \bullet$, then the colimit over I is called the *pushout*. The limit over $I^{\text{op}} = \bullet \rightarrow \bullet \leftarrow \bullet$ is called the *pullback*. We denote these by

$$\begin{array}{ccc} Z & \longrightarrow & Y \\ \downarrow & \lrcorner & \downarrow \\ X & \longrightarrow & X \amalg_Z Y \end{array} \quad \begin{array}{ccc} X \times_Z Y & \longrightarrow & Y \\ \downarrow & \lrcorner & \downarrow \\ X & \longrightarrow & Z. \end{array}$$

Examples 2.46. Here are some examples of pushouts:

- In Set , the pushout

$$\begin{array}{ccc} Z & \xrightarrow{f} & Y \\ g \downarrow & \lrcorner & \downarrow i_2 \\ X & \xrightarrow{i_1} & X \amalg_Z Y \end{array}$$

is given by $X \amalg_Z Y = (X \amalg Y) / (i_1 f(z) \sim i_2 g(z))$.

If $X, Y \subseteq S$ are both subsets of some larger set with $X \cap Y = Z$, then the pushout is $X \cup Y$.

- In Top the pushout is a gluing construction

$$\begin{array}{ccc} Z & \xrightarrow{f} & Y \\ \downarrow & \lrcorner & \downarrow \\ X & \longrightarrow & X \cup_Z Y, \end{array}$$

where $Z \rightarrow X$ is some nice map like a closed inclusion, then we have that

$$X \cup_f Y = X \cup_f Y = X \amalg Y / f(z) \sim z.$$

For example, given the boundary inclusion $S^1 \rightarrow D^2$, we have that

$$\begin{array}{ccc} S^1 & \hookrightarrow & D^2 \\ \downarrow & \lrcorner & \downarrow \\ D^2 & \longrightarrow & S^2. \end{array}$$

- In **Set**, the pullback

$$\begin{array}{ccc} X \times_Z Y & \longrightarrow & Y \\ \downarrow & \lrcorner & \downarrow \\ X & \longrightarrow & Z \end{array}$$

is given by

$$X \times_Z Y := \{(x, y) \in X \times Y : f(x) = g(y)\}.$$

For example, given the parity map $\mathbb{Z} \rightarrow \mathbb{Z}/2$, the pullback along the trivial map from 0 is:

$$\begin{array}{ccc} 2\mathbb{Z} & \longrightarrow & \mathbb{Z} \\ \downarrow & \lrcorner & \downarrow \\ 0 & \longrightarrow & \mathbb{Z}/2. \end{array}$$

More generally, given $f : X \rightarrow A$, the pullback of f along the inclusion $* \rightarrow A$ which picks out a point $a \in A$ is given by:

$$\begin{array}{ccc} f^{-1}(a) & \longrightarrow & A \\ \downarrow & \lrcorner & \downarrow f \\ * & \xrightarrow[a]{} & X \end{array}$$

Example 2.47. Recall that a CW complex X has a discrete set X_0 and has skeleta X_{n+1} which is built from X_n via a pushout diagram

$$\begin{array}{ccc} \coprod_\alpha S^n & \longrightarrow & \coprod_\alpha D^{n+1} \\ \coprod_\alpha f_\alpha \downarrow & \lrcorner & \downarrow \\ X_n & \longrightarrow & X_{n+1}. \end{array}$$

where $\coprod_\alpha f_\alpha$ are the attaching maps. Then we define

$$X = \bigcup_n X_n = \text{colim } (X_0 \rightarrow X_1 \rightarrow \dots)$$

with the *weak topology*, meaning that $A \subseteq X$ is closed if and only if $A \cap X_n$ is closed for each n .

Proposition 2.48. CW complexes are in CGWH.

Note 2.49. The product of CW complexes $X \times Y$ gets a cell structure with n -cells of $X \times Y$ corresponding to a p -cell of X and a q -cell of Y where $p + q = n$. The idea behind this is that

$$D^{p+q} \cong I^{p+q} \cong I^p \times I^q \cong D^p \times D^q.$$

The issue is that the product of two CW complexes $X \times Y$ is only a CW complex if the product topology is the same as the weak topology. We also note that the product topology is generally not as fine as the weak topology.

There were some partial results known before the introduction of CGWH spaces.

1. Whitehead '49 showed that if X and Y are CW complexes, and one is locally finite, then $X \times Y$ is CW
2. Milnor '56 showed that if both are locally countable, then $X \times Y$ is CW
3. Tanaka '82 counterexample: if X and Y are CW and neither are locally countable, then $X \times Y$ is *not* CW.

citation needed

But the good news is that in CGWH we have that $X \times_k Y$ is always a CW complex. A proof can be found in [?, Theorem A.6].

2.5 Existence of limits and colimits in Top

Definition 2.50. A category with all limits is called *complete*, and a category with all colimits is called *cocomplete*.

We start with a remark about a way to describe limits when they exist.

Remark 2.51. We may check that, in any \mathcal{C} which has J -shaped limits,

$$\text{Hom}_{\mathcal{C}}(Z, \lim_J F) \cong \text{Hom}_{\mathcal{C}^J}(\Delta Z, F)$$

where $\Delta : \mathcal{C} \rightarrow \mathcal{C}^J$ is the diagonal functor which sends c to the constant diagram at c .

Proposition 2.52. If \mathcal{C} has arbitrary coproducts and coequalizers, then it is cocomplete. Dually, if \mathcal{C} has arbitrary products and equalizers, then it is complete.

Proposition 2.53. Top is complete and cocomplete.

Proof idea. Note that we have coproducts given by disjoint union, and coequalizers are given by quotients

$$\text{coeq} \left(X \begin{smallmatrix} f \\ \rightrightarrows \\ g \end{smallmatrix} Y \right) := X / f(x) \sim g(x).$$

Products are given by products, and we may check that equalizers are a subspace given by equality of two functions.

□

Proposition 2.54. The category CGWH is complete and cocomplete.

Proof. Recall that we had adjunctions

$$\text{Top} \underset{i}{\overset{k}{\rightleftarrows}} \text{CG} \underset{h}{\overset{j}{\rightleftarrows}} \text{CGWH},$$

where the right adjoints are displayed on top.

1. We have that i preserves colimits, so colimits of CG spaces are computed in Top when they exist. So we must check that coequalizers and coproducts of CG spaces are CG (exercise).

For limits, we claim that $\lim_J D$ for $D: J \rightarrow \text{CG}$ is $k \lim_J (i \circ D)$ in CG . First note that

$$\text{Hom}_{\text{CG}}(X, k \lim_J (i \circ D)) \cong \text{Hom}_{\text{Top}}(iX, \lim_J (i \circ D)).$$

Using ??, we have that

$$\begin{aligned} \text{Hom}_{\text{Top}}(iX, \lim_J (i \circ D)) &\cong \text{Hom}_{\text{Top}^J}(\Delta(iX), iD) \\ &\cong \text{Hom}_{\text{Top}^J}(i \circ \Delta X, iD) \\ &\cong \text{Hom}_{\text{CG}^J}(\Delta X, k \circ iD) \\ &\cong \text{Hom}_{\text{CG}^J}(\Delta X, D), \end{aligned}$$

where this last isomorphism is since D already takes values in CG . Finally, we see that

$$\text{Hom}_{\text{CG}^J}(\Delta X, D) \cong \text{Hom}_{\text{CG}}(X, \lim_J D).$$

Since this is true for all objects X , we may check that $k \lim_J (i \circ D) = \lim_J D$.

Upshot: We have that CG is complete and cocomplete and we know how to compute limits and colimits:

- colimits: do nothing except compute them in Top
 - limits: just apply $k(-)$ to it.
2. Since j preserves limits, we have that CGWH is complete if all limits of CG spaces exist in CGWH . We must check this on products and equalizers (exercise). For colimits, we need to apply h to the colimit in CG , similarly to as we did above.

So we have that CGWH is complete, cocomplete, and cartesian closed. \square

Notation 2.55. From here on we redefine the category of topological spaces to be $\text{Top} := \text{CGWH}$, and redefine $\times := \times_k$, $\text{Map} := k\text{Map}$.

2.6 The category of based topological spaces

Let Top_* be the category of based (CGWH) spaces and based maps. Let $\text{Map}_*(X, Y)$ be the space of based maps, and note that we may base this mapping space at the constant map sending every $x \in X$ to the basepoint y_0 of Y .

The functor $\text{Map}_*(X, -)$ has an adjoint, but it is not given by the product! Instead, the functor $X \wedge -$ is an adjoint. We can verify that, for any other based spaces Y and Z we have a natural isomorphism

$$\text{Hom}_{\text{Top}_*}(Y \wedge X, Z) \cong \text{Hom}_{\text{Top}_*}(Y, \text{Map}_*(X, Z)).$$

Lemma 2.56. There exist natural isomorphisms

1. $(X \wedge Y) \wedge Z \cong X \wedge (Y \wedge Z)$
2. $X \wedge Y \cong Y \wedge X$
3. $X \wedge S^0 \cong X \cong S^0 \wedge X.$

Proof idea. For (1), it is important that we are in CGWH. By [?, Proposition 2.20], products preserve quotients, so that the first map in the following composite is a quotient

$$X \times Y \times Z \rightarrow (X \wedge Y) \times Z \rightarrow (X \wedge Y) \wedge Z.$$

Since the composite of quotient maps is a quotient map, it may be identified with the quotient

$$X \times Y \times Z \rightarrow \frac{X \times Y \times Z}{X \vee Y \vee Z}.$$

Thus it does not depend on the order. □

We remark that the associativity isomorphism does not hold in the category of all topological spaces. A counterexample is given by $(\mathbb{N} \wedge \mathbb{Q}) \wedge \mathbb{Q}$ which is not homeomorphic to $\mathbb{N} \wedge (\mathbb{Q} \wedge \mathbb{Q})$. For a discussion see this [mathoverflow post](#).

Definition 2.57. A *symmetric monoidal category* is a triple $(\mathcal{C}, \otimes, \mathbb{1})$, where \mathcal{C} is a category, $\mathbb{1} \in \mathcal{C}$ is an object, and \otimes is a bifunctor

$$- \otimes - : \mathcal{C} \times \mathcal{C} \rightarrow \mathcal{C},$$

such that there are natural isomorphisms

$$\begin{aligned} (c \otimes d) \otimes e &\cong c \otimes (d \otimes e) \\ c \otimes d &\cong d \otimes c \\ \mathbb{1} \otimes c &\cong c \cong c \otimes \mathbb{1}, \end{aligned}$$

for any objects in \mathcal{C} , such that all possible diagrams involving these commute (infinite data, really hard to check). However by MacLane's coherence theorem, we only need to check a few diagrams (in particular, the pentagon), and it then follows that all higher diagrams commute.

Definition 2.58. A symmetric monoidal category is *closed* if $- \otimes X$ has an adjoint for all X .

Proposition 2.59. $(\text{Top}_*, \wedge, S^0)$ is a closed symmetric monoidal category.

We end with a definition that we don't fully spell out, but which we will encounter over and over again in this class.

Definition 2.60. Let \mathcal{V} be a symmetric monoidal category. We say that a category \mathcal{C} is enriched in \mathcal{V} if each $\text{Hom}_{\mathcal{C}}(c, d)$ is an object of \mathcal{V} , the composition is given by a map

$$\text{Hom}_{\mathcal{C}}(c, d) \otimes \text{Hom}_{\mathcal{C}}(b, c) \rightarrow \text{Hom}_{\mathcal{C}}(b, d)$$

in \mathcal{V} , and there are unit maps $1 \rightarrow \text{Hom}_{\mathcal{C}}(c, c)$, such that the appropriate associativity and unitality diagrams commute.

Example 2.61. The main example we have already encountered is Top , which is enriched over itself since the mapping spaces carry a topology. Moreover we have seen that the $- \times X$ and $\text{Map}(X, -)$ adjunction is an enriched adjunction (the isomorphisms of hom sets were actually homeomorphisms of mapping spaces).

3 Higher homotopy groups

3.1 Homotopies

Recall for $f, g : X \rightarrow Y$, a *homotopy* h from f to g is a map

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

such that $h(x, 0) = f(x)$, and $h(x, 1) = g(x)$ for all $x \in X$. We write $f \simeq g$ to denote the homotopy.

Definition 3.1. Let $[X, Y]$ be the set of homotopy equivalence classes of maps $X \rightarrow Y$ (check that \simeq gives an equivalence relation).

Proposition 3.2. Let $X, Y \in \text{Top}$. Then there is a bijection

$$[X, Y] \xrightarrow{\cong} \pi_0 \text{Map}(X, Y).$$

Proof. We note that

$$\text{Map}(I \times X, Y) \cong \text{Map}(I, \text{Map}(X, Y)),$$

so a homotopy $f \simeq g$ corresponds to a path between f and g in the mapping space $\text{Map}(X, Y)$. \square

Definition 3.3. We say that two spaces are *homotopy equivalent* if there exist maps $f : X \rightarrow Y$ and $g : Y \rightarrow X$ such that $f \circ g \simeq \text{id}_Y$ and $g \circ f \simeq \text{id}_X$.

Exercise 3.4. Show that \simeq is an equivalence relation on objects in Top .

Proposition 3.5. Homotopy equivalence satisfies “2 out of 3”: meaning if two out of the maps $f, g, g \circ f$ are homotopy equivalences, then so is the third (check).

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ & \searrow g \circ f & \downarrow g \\ & & Z. \end{array}$$

Note 3.6. The property “2 out of 3” holds automatically for all categorical isomorphisms.²

Definition 3.7. A space X is *contractible* if it is homotopy equivalent to a point (e.g. I , D^n , \mathbb{R}^n , S^∞ , ...).

Definition 3.8. The *cone* on X is defined to be the quotient space $CX := \frac{X \times I}{X \times \{1\}}$.

Exercise 3.9.

1. Show X is contractible if and only if id_X is null-homotopic (homotopic to a constant map)
2. Show that $f : S^n \rightarrow Y$ is null-homotopic if and only if there exists an extension of f to the closed disk

$$\begin{array}{ccc} S^n & \xrightarrow{f} & Y \\ \downarrow & \nearrow \tilde{f} & \\ D^{n+1} & & \end{array}$$

3. More generally, show that $f : X \rightarrow Y$ is null-homotopic if and only if there exists an extension

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \downarrow & \nearrow \tilde{f} & \\ CX & & \end{array}$$

Definition 3.10. A *based homotopy* from f to g , where $f, g : (X, x_0) \rightarrow (Y, y_0)$ is a homotopy $h : f \simeq g$ with the extra condition that each $h(-, t) : (X, x_0) \rightarrow (Y, y_0)$ is based.

We should check that this is equivalent to a based map $h : X \wedge I_+ \rightarrow Y$.

Notation 3.11. The set of based homotopy equivalence classes of maps is denoted $[X, Y]_*$. For example, $[S^1, (X, x_0)]_* = \pi_1(X, x_0)$.

3.2 The homotopy category of spaces

Definition 3.12. The *homotopy category of Top*, denoted $\text{Ho}(\text{Top})$, is the category whose objects are topological spaces, and whose morphisms are given by

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

An isomorphism in $\text{Ho}(\text{Top})$ is the equivalence class of a homotopy equivalence $X \rightarrow Y$.

There exists an obvious functor $\text{Top} \xrightarrow{\sim} \text{Ho}(\text{Top})$ sending a map to its equivalence class.

²In fact, the class of isomorphisms satisfies a stronger property, called *2-out-of-6*.

Proposition 3.13. The functor $\gamma: \text{Top} \rightarrow \text{Ho}(\text{Top})$ is universal among functors $F: \text{Top} \rightarrow \mathcal{C}$ which send homotopy equivalences into isomorphisms.³ That is, for any such functor, it factors uniquely as

$$\begin{array}{ccc} \text{Top} & \xrightarrow{F} & \mathcal{C} \\ \gamma \downarrow & \nearrow \exists! & \\ \text{Ho}(\text{Top}) & & \end{array}$$

Proof. We will define $\varphi_F: \text{Ho}(\text{Top}) \rightarrow \mathcal{C}$ on objects to be $\varphi_F(X) = F(X)$. For a morphism $f: X \rightarrow Y$ in Top , define $\varphi_F([f]) = F(f)$.

To see that this is well-defined, suppose $g \simeq f$. Then there exists $h: X \times I \rightarrow Y$ such that $h \circ i_0 = f$ and $h \circ i_1 = g$, where $i_0, i_1: X \rightarrow X \times I$ are the inclusions at time 0 and 1. Let $\pi_X: X \times I \rightarrow X$ be the projection on X , and note that i_0, i_1, π_X are all homotopy equivalences. Therefore $F(i_0), F(i_1), F(\pi_X)$ are all isomorphisms. We note also that

$$\pi_X \circ i_0 = \text{id}_X = \pi_X \circ i_1.$$

Thus

$$F(\pi_X) \circ F(i_0) = \text{id}_{F(X)} = F(\pi_X) \circ F(i_1).$$

Since $F(\pi_X)$ is an isomorphism, we cancel it to see $F(i_0) = F(i_1)$. Then

$$F(g) = F(h) \circ F(i_1) = F(h) \circ F(i_0) = F(f).$$

Thus φ_F is well-defined, and we may check that it is a functor, and that it is unique (exercise). \square

Similarly, we may define $\text{Ho}(\text{Top}_*)$ whose objects are based spaces, and whose morphisms are given by

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

which are the classes of based maps under based homotopy. We note that $[X, Y]_*$ is canonically based at the class of the constant map at the basepoint on Y , and composition is a map of based sets.⁴

In algebraic topology, or in homotopy theory, we always want functors from Top or Top_* to some category of algebraic objects (Grp , Ab , Ring) which factor through the homotopy category.

Warning 3.14. The categories $\text{Ho}(\text{Top})$ and $\text{Ho}(\text{Top}_*)$ do not have all limits and colimits.

³For example, any homotopy invariant functor F , meaning $F(f) = F(g)$ if $f \simeq g$ sends homotopy equivalences to isomorphisms.

⁴We may say then that $\text{Ho}(\text{Top}_*)$ is enriched over Set_* .

3.3 Higher homotopy groups

Definition 3.15. For $n \geq 1$, the higher homotopy groups are defined to be

$$\pi_n(X, x_0) = [S^n, (X, x_0)]_*.$$

For $n = 0$, the same definition gives classes of based maps $S^0 \rightarrow X$, which correspond to path components of X . Thus $\pi_0(X, x_0)$ is a based set. We need to prove that $\pi_n(X, x_0)$ are groups. You have already seen the proof for $n = 1$, i.e. for the fundamental group, in a first algebraic topology course. For all the higher homotopy groups we will have an even stronger result: we will see that $\pi_n(X, x_0)$ are abelian groups for all $n \geq 2$.

For $n = 1$, we think of S^1 as $I^1/\partial I^1$. Then we recall the *pinch map* is given by

$$p : S^1 \rightarrow S^1 \vee S^1$$

$$p(x) = \begin{cases} 2x & 0 \leq x \leq \frac{1}{2} \\ 2x - 1 & \frac{1}{2} \leq x \leq 1. \end{cases}$$

This is used to define the group structure

$$\pi_1(X) \times \pi_1(X) = [S^1, X]_* \times [S^1, X]_* \cong [S^1 \vee S^1, X]_* \xrightarrow{- \circ p} [S^1, X]_* = \pi_1(X).$$

We may verify that this is a group. So π_1 is a functor to \mathbf{Grp} .

For $n \geq 2$, we note that $S^n \cong S^1 \wedge \cdots \wedge S^1$ is n copies of the 1-sphere smashed together.

Exercise 3.16. $(X \vee Y) \wedge Z \cong (X \wedge Z) \vee (Y \wedge Z)$.

Proof. Left adjoints preserve colimits, and note that $- \wedge Z : \mathbf{Top}_* \rightarrow \mathbf{Top}_*$ is a left adjoint. \square

Thus we can define n different pinch maps:

$$p_1 : S^n \cong S^1 \wedge S^{\wedge(n-1)} \xrightarrow{p \wedge \text{id}} (S^1 \vee S^1) \wedge S^{n-1} = S^n \vee S^n$$

$$\vdots$$

$$p_k : S^n \cong S^{k-1} \wedge S^1 \wedge S^{n-k} \xrightarrow{\text{id} \wedge p \wedge \text{id}} S^{k-1} \wedge (S^1 \vee S^1) \wedge S^{n-k} \cong S^n \vee S^n$$

$$\vdots$$

where we apply the pinch map p to any one of the n factors. A priori, this seems troubling, since it seems to indicate that we may form n different multiplications on $\pi_n(X)$ for each space X .

Lemma 3.17. (Eckmann-Hilton argument) Suppose that a set X has two binary operations \bullet and $*$ such that

1. they both have the same unit e

2. the following interchange law holds for all $x, y, z, w \in X$:

$$(x \bullet y) * (z \bullet w) = (x * z) \bullet (y * w).$$

Then $\bullet = *$ and they are both commutative.

Proof. Using the unit and the interchange law,

$$\begin{aligned} (x \bullet y) &= (x * e) \bullet (e * y) \\ &= (x \bullet e) * (e \bullet y) \\ &= x * y. \end{aligned}$$

To see commutativity,

$$\begin{aligned} x \bullet y &= (e * x) \bullet (y * e) \\ &= (e \bullet y) * (x \bullet e) \\ &= y * x \\ &= y \bullet x. \end{aligned}$$

□

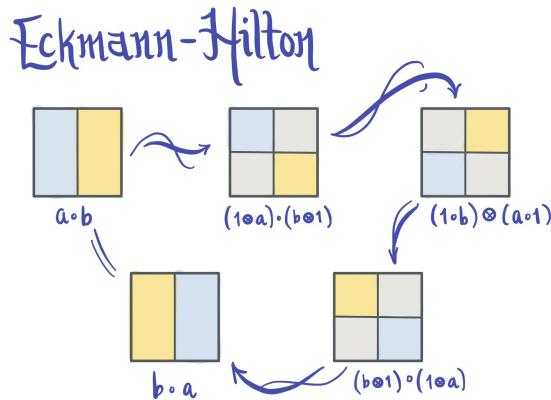


Figure 4: Eckmann-Hilton proof of commutativity in pictures.

Corollary 3.18. For $n \geq 2$, all the multiplications on $\pi_n(X)$ defined above are the same, and they are commutative.

Proof. Suppose we have two maps $f, g : S^n \rightarrow X$. We can think of these as maps $f, g : I^n \rightarrow X$ such that $f(\partial I^n) = x_0 = g(\partial I^n)$. Then, using the pinch maps on the first and second factor, we

define

$$f \bullet g = \begin{cases} f(2x_1, x_2, \dots, x_n) & 0 \leq x_1 \leq \frac{1}{2} \\ g(2x_1 - 1, x_2, \dots, x_n) & 0 \leq x_1 \leq \frac{1}{2} \end{cases}$$

$$f * g = \begin{cases} f(x_1, 2x_2, \dots, x_n) & 0 \leq x_s \leq \frac{1}{2} \\ g(x_1, 2x_2 - 1, \dots, x_n) & 0 \leq x_2 \leq \frac{1}{2} \end{cases}$$

Then we may check that

$$(f \bullet g) * (h \bullet i)(x_1, \dots, x_n) = (f * h) \bullet (g * i)(x_1, \dots, x_n)$$

$$= \begin{cases} f(2x_1, 2x_2, x_3, \dots, x_n) & (x_1, x_2) \in [0, \frac{1}{2}] \times [0, \frac{1}{2}] \\ g(2x_1 - 1, 2x_2, x_3, \dots, x_n) & (x_1, x_2) \in [\frac{1}{2}, 1] \times [0, \frac{1}{2}] \\ h(2x_1, 2x_2 - 1, x_3, \dots, x_n) & (x_1, x_2) \in [0, \frac{1}{2}] \times [\frac{1}{2}, 1] \\ i(2x_1 - 1, 2x_2 - 1, x_3, \dots, x_n) & (x_1, x_2) \in [\frac{1}{2}, 1] \times [\frac{1}{2}, 1]. \end{cases}$$

Thus $*$ and \bullet are both equal and commutative.

□

Topologists of the early 20th century were aware that the noncommutative nature of the fundamental group was useful in geometry and analysis; that the first homology group was, for a connected space, the fundamental group made abelian; and that the homology groups were defined in all dimensions. Consequently, there was a desire to find higher dimensional versions of the fundamental group, keeping its nonabelian nature.

In 1932, E. Cech submitted to the ICM at Zurich a paper on higher homotopy groups; however, Alexandroff and Hopf, the kings of topology at the time, objected to the fact that they were abelian for $n \geq 2$, and on these grounds persuaded Cech to withdraw his paper, so that only a small paragraph appeared in the ICM Proceedings.

It seems that Hurewicz attended this ICM. In 1935, the first of his notes on homotopy groups was published, and from then the concerns about the abelian nature of higher homotopy groups were regarded as a failure to accept a basic fact of life.

[?]

3.4 Dependence of π_k on the basepoint

We are mostly following the proof in [?, Chapter 4]. A good exposition is also given [?, Section 3].

Recall: The homology groups H_n do not depend on the basepoint, so if we expect some relation between π_n and H_n , we might expect that π_n does not depend on the basepoint up to isomorphism (at least for X path-connected).

Consider the forgetful map

$$[S^n, (X, x_0)]_* \rightarrow [S^n, X].$$

When is this surjective? That is, given $f : S^n \rightarrow X$, is it homotopic to a based map?

We would note that such a homotopy gives a path from $f(*)$ to the basepoint, so we certainly need X to be path-connected.

Claim: If X is path-connected, then any two choices of basepoint give isomorphic homotopy groups. This is why we generally write $\pi_n(X)$, omitting the basepoint.

Proposition 3.19. Let X be path-connected, with points $x, y \in X$. Then

$$\pi_n(X, x) \cong \pi_n(X, y).$$

Proof. Consider any map representing a class $[f] \in \pi_n(X, y)$ as a map $f : I^n \rightarrow X$ sending ∂I^n to y . Let γ denote a path from y to x . Let $J = [\epsilon, 1 - \epsilon] \subset I$, where $\epsilon \in (0, \frac{1}{2})$, and so that J^n is a smaller cube inside I^n , as depicted in ???. From each point on ∂I^n , draw a line segment to the center of I^n , which intersects ∂J^n . Consider the radial segments from ∂I^n to ∂J^n defined by these lines. Now reparametrize f , so that its domain is J^n . Note that on ∂J^n , f is then identically y .

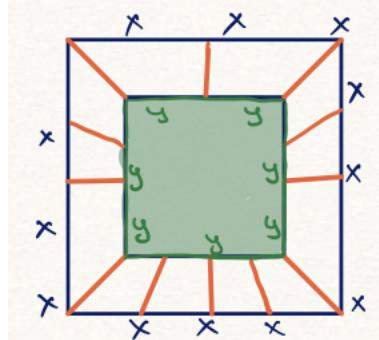


Figure 5: J^n inside I^n , to be replaced with Maxine's professional pic

Now we can define the change of basepoint map

$$\begin{aligned} \gamma \cdot \pi_n(X, y) &\rightarrow \pi_n(X, x) \\ [f] &\mapsto [\gamma \cdot f]. \end{aligned}$$

We define $\gamma \cdot f : I^n \rightarrow X$ as follows:

- For $z \in J^n$, let $(\gamma \cdot f)(z) = f(z)$, where we are using the reparametrized f with domain shrunk to J^n . So note that $(\gamma \cdot f)(\partial J^n) = y$.

- For z lying on one of the radial segments, let $(\gamma \cdot f)(z) = \gamma(z)$, where we have reparametrized the radial segment from ∂J^n to ∂I^n to coincide with I , so that on each radial segment we can apply the map $\gamma: I \rightarrow X$.

Note that this assignment is continuous since $(\gamma \cdot f)(\partial J^n) = y$, and $\gamma(0) = y$. Also note that $(\gamma \cdot f)(\partial I^n) = x$.

We can check that it is well-defined (can reparametrize homotopies). Now to show it is a homomorphism, let $f, g \in \pi_n(X, y)$. We let $f + 0$ be f , reparametrized to have domain $x_1 \leq \frac{1}{2}$ and be constantly equal to y on the other half. We let $0 + g$ be g reparametrized in the same way, but with domain $x_1 \geq \frac{1}{2}$. We note that these reparametrizations do not affect the homotopy class, so $f + 0 \simeq f$ and $0 + g \simeq g$. We claim then that

$$\gamma \cdot f + \gamma \cdot g \simeq \gamma \cdot (f + 0) + \gamma \cdot (0 + g) \simeq \gamma \cdot (f + g).$$

The second homotopy is given by

$$h_t(x_1, \dots, x_n) = \begin{cases} \gamma \cdot (f + 0)((2-t)x_1, x_2, \dots, x_n) & x_1 \in [0, \frac{1}{2}] \\ \gamma \cdot (0 + g)((2-t)x_1 + t - 1, x_2, \dots, x_n) & x_1 \in [\frac{1}{2}, 1] \end{cases}$$

We check that these are the same at $x_1 = \frac{1}{2}$, that is

$$\gamma \cdot (f + 0)(1 - \frac{t}{2}, x_2, \dots,) \stackrel{?}{=} \gamma \cdot (0 + g) \left(\frac{t}{2}, x_2, \dots, \right)$$

If $t/2 > \epsilon$, then both are y . If $t/2 < \epsilon$, both are the same point on γ .

We also get (by reparametrizing) that $(\gamma \eta) \cdot f \simeq \gamma \cdot (\eta \cdot f)$ and $c \cdot f \simeq f$, where c is a constant path. In particular, this shows that $\gamma^{-1} \cdot$ is an inverse isomorphism to $\gamma \cdot$. \square

Note 3.20. Note that we can apply this for based loops at x . Then the formulae above define an action of $\pi_1(X, x)$ on $\pi_n(X, x)$. For $n = 1$, this is just the conjugation action in $\pi_1(X, x)$, which is generally nontrivial when $\pi_1(X, x)$ is nonabelian.

Note 3.21. If X is not simply connected, the isomorphism $\gamma \circ -$ is not canonical.

Note 3.22. For a non-contractible loop γ based at x , our isomorphism

$$\gamma \cdot - : \pi_n(X, x) \xrightarrow{\cong} \pi_n(X, x)$$

is not the identity. Thus we note that $\pi_n(X, x)$ is defined only up to isomorphism without a choice of basepoint. However if $\pi_1(X, x)$ is trivial, then $\pi_n(X)$ is well-defined without a choice of basepoint.

3.5 Weak homotopy equivalence

Definition 3.23. A map $f: X \rightarrow Y$ is a *weak homotopy equivalence* if, for every choice of basepoint $x \in X$, the induced maps

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

are group isomorphisms for $n \geq 1$ and a bijection for $n = 0$.

Note 3.24. If X and Y are path-connected, it is sufficient to require that $f_* : \pi_n(X, x) \rightarrow \pi_n(Y, f(x))$ is an isomorphism for all $n \geq 1$ and for all $x \in X$.

Proposition 3.25. A homotopy equivalence $f : X \rightarrow Y$ is a weak homotopy equivalence.

Proof. We first check that f induces a bijection on path components, and moreover that f restricts to a homotopy equivalence on each path component (exercise). We now restrict to the case where X and Y are path-connected.

Let $g : Y \rightarrow X$ be the homotopy inverse to f , and suppose that $x \in X$ is a given basepoint. Consider the composite

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

We know that $g \circ f \simeq \text{id}_X$, however this is not necessarily a based homotopy. Let γ be the path from $gf(x)$ to x defined by the homotopy. Letting γ act on $\pi_n(X, gf(x))$, we get a composite

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

which we claim is the identity. This follows from the following more general ??.

By 2-out-of-3 for group isomorphisms, we must have that $g_* \circ f_*$ is an isomorphism, and we have that f_* is injective.

Finally, by a symmetric argument, one may show that f_* is surjective by proving that $f_* \circ g_*$ is an isomorphism. \square

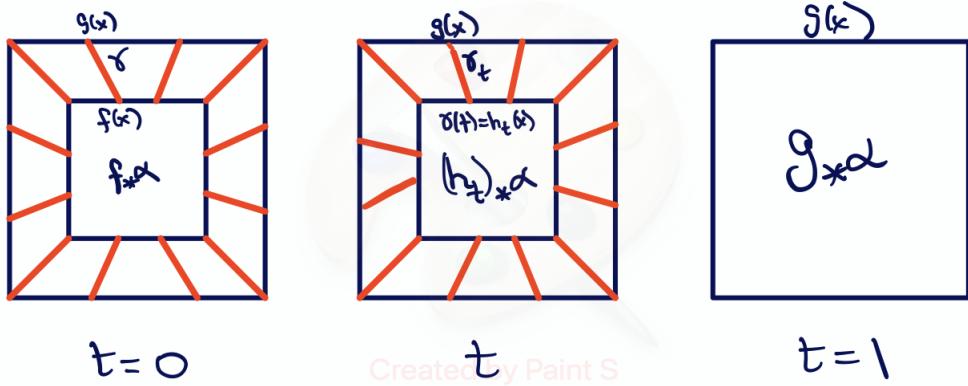
Lemma 3.26. Suppose $f, g: X \rightarrow Y$ are homotopic maps via a homotopy h . Let γ be the path given by $h_t(x)$ from $f(x)$ to $g(x)$. Then the following diagram commutes.

$$\begin{array}{ccc} \pi_n(X, x) & \xrightarrow{f_*} & \pi_n(Y, f(x)) \\ & \searrow g_* & \downarrow \gamma \\ & & \pi_n(Y, g(x)) \end{array}$$

Proof. Exercise, generalizing the case $n = 1$, which appears as [?, Proposition 1.18]. Suppose $f \simeq_h g$ and $\alpha: I^n / \partial I^n \rightarrow X$. Let γ be a path from $f(x)$ to $g(x)$ and for any fixed t , let γ_t be the path from $\gamma(t)$ to $g(x)$, reparametrized over I .



Figure 6: Definition of γ_t

Figure 7: A homotopy from $\gamma \cdot (f_* \alpha)$ to $g_*(\alpha)$

Here is a pictorial proof, generalizing that for $n = 1$ in Hatcher:

□

The converse to ?? does not hold. Here are two famous counterexamples.

Example 3.27. Consider the *topologist's sine curve*

$$X = \{(x, \sin \frac{1}{x}) : 0 < x \leq 1\} \cup (\{0\} \times [-1, 1]).$$

This space is connected but not path-connected. Let's base X at $x = (0, 1)$, and take a based map

$$\begin{aligned} f: (S^0, 0) &\rightarrow X \\ 0 &\mapsto x \\ 1 &\mapsto (1, \sin(1)). \end{aligned}$$

This is a weak equivalence but not a homotopy equivalence.

Example 3.28. The pseudo circle is a finite topological space $X = \{a, b, c, d\}$, with topology given by $\{\{a, b, c, d\}, \{a, b, c\}, \{a, b, d\}, \{a, b\}, \{a\}, \{b\}\}$. It turns out that this space is indistinguishable from the circle when it comes to weak equivalence. Consider the map $f: S^1 \rightarrow X$ which sends the north pole to c , the south pole to d , the left hemisphere to a and the right hemisphere to b .

This map is continuous, and it induces an isomorphism on all homotopy groups. However, there is no inverse homotopy equivalence.

Proposition 3.29. The weak equivalences satisfy 2-out-of-3.

Proof. Suppose we are given maps

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ & \searrow h & \downarrow g \\ & & Z. \end{array}$$

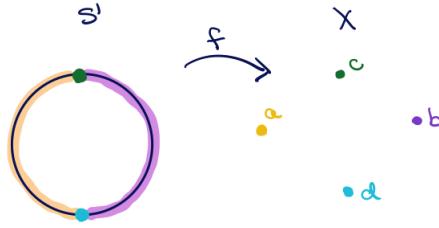


Figure 8: The map from the circle to the pseudo circle

We claim that if f and h are weak equivalences, then so is g . Let $y \in Y$ be a chosen basepoint. If $y \in \text{im}(f)$, then we are done. If not, then see that since f induces a bijection on path-components, there is a point $y_0 \in \text{im}(f)$ and a path γ between y and y_0 . Then by ?? we have isomorphisms

$$\pi_n(Y, y) \xrightarrow{\cong} \pi_n(Y, y_0),$$

and

$$\pi_n(Z, g(y)) \xrightarrow{\cong} \pi_n(Z, g(y_0)).$$

Thus the diagram commutes

$$\begin{array}{ccc} \pi_n(Y, y) & \xrightarrow{g} & \pi_n(Z, g(y)) \\ \downarrow \cong & & \downarrow \cong \\ \pi_n(Y, y_0) & \xrightarrow[\cong]{} & \pi_n(Z, g(y_0)), \end{array}$$

and since all the other maps are isomorphisms, we see that $g: \pi_n(Y, y) \rightarrow \pi_n(Z, g(y))$ is an isomorphism.

□

4 Fiber and cofiber sequences of spaces

We might ask: is there a notion of sequence of spaces which induces long exact sequences in homotopy groups or (co)homology groups. In this section we will make sense of such notions of “exact sequences” in spaces.

4.1 Cofibrations

Consider an inclusion $i: A \hookrightarrow X$ where $A \simeq *$. Is $X/A \simeq X$? In general no, but if the inclusion is “nice,” then yes. Cofibrations are precisely “nice” inclusions.

Definition 4.1. A map $i : A \rightarrow X$ satisfies the *homotopy extension property* if for any given map $X \xrightarrow{f} Y$ and homotopy $A \times I \xrightarrow{h} Y$, with $h_0 = f \circ i$, then there exists an extension $\tilde{h} : X \times I \rightarrow Y$ such that $\tilde{h}(i \times \text{id}) = h$ and $\tilde{h}_0 = f$. Diagrammatically,

$$\begin{array}{ccc} A & \xrightarrow{i_0} & A \times I \\ i \downarrow & \nearrow f & \swarrow h \\ X & \xrightarrow{i_0} & X \times I \end{array}$$

$\nwarrow \tilde{h} \quad \searrow \kappa$

Via our adjunction $\text{Hom}(A \times I, Y) \cong \text{Hom}(A, Y^I)$, we can translate our test diagram to a simpler diagram that looks as follows

$$\begin{array}{ccc} A & \xrightarrow{h} & Y^I \\ i \downarrow & \nearrow \tilde{h} & \downarrow \text{ev}_0 \\ X & \xrightarrow{f} & Y. \end{array}$$

Figure 9: HEP test diagram for $i : A \rightarrow X$

A map which satisfies HEP is called a *cofibration* (or *h-cofibration*). We denote cofibrations “ \rightarrowtail ” as arrows with tails.

Note 4.2. We have a universal example of such a lifting diagram. Given the data $f : X \rightarrow Y$ and $h : A \times I \rightarrow Y$ starting at $f \circ i$, we obtain a map from the space defined via the pushout

$$\begin{array}{ccc} A & \xrightarrow{i_0} & A \times I \\ i \downarrow & \lrcorner & \downarrow \\ X & \xrightarrow{f} & Mi \\ & \searrow & \swarrow h \\ & & Y \end{array}$$

The pushout Mi is called the *mapping cylinder* of the map i . We get a factorization

$$\begin{array}{ccccc} A & \longrightarrow & Mi^I & \longrightarrow & Y^I \\ \downarrow & \nearrow & \downarrow \text{ev}_0 & \downarrow \text{ev}_0 & \\ X & \longrightarrow & Mi & \longrightarrow & Y \end{array}$$

Therefore it suffices to find a lift $X \rightarrow Mi^I$ in order to get our lift $X \rightarrow Y^I$.

Exercise 4.3.

1. If $i : A \hookrightarrow X$ is a cofibration, it is a closed inclusion.
2. A map $i : A \rightarrow X$ is a cofibration if and only if Mi is a retract of $X \times I$.

The first part is an exercise in [?] and is worked out in this [mathoverflow post](#) (see Peter May's comment).

Here are some examples of cofibrations, which you have likely encountered:

- The unbased inclusion $\emptyset \xhookrightarrow{i} X$ for any space X
- The inclusions $\{0\} \hookrightarrow I$ or $\partial I \hookrightarrow I$ for the interval $[0, 1]$
- $S^{n-1} \hookrightarrow D^n$
- $S^{n-1} \hookrightarrow S^n$ equator embedding
- All identities
- All homeomorphisms.

Proposition 4.4. The class of cofibrations is closed under:

1. composition
2. pushouts
3. retracts
4. finite coproducts
5. sequential colimits

Proof. For (1), suppose we have a composite $A \xrightarrow{i} B \xrightarrow{j} C$ of cofibrations, and consider a test diagram,

$$\begin{array}{ccc} A & \xrightarrow{h} & Y^I \\ i \downarrow & \nearrow \tilde{h}_1 & \downarrow \\ B & & \\ j \downarrow & \nearrow \tilde{h}_2 & \downarrow \text{ev}_0 \\ C & \xrightarrow{\quad} & Y \end{array}$$

where we note that \tilde{h}_1 exists by the top diagram, and we note that $\tilde{h}_2 : C \rightarrow Y^I$ exists via the bottom diagram.

For (2), suppose $A \xhookrightarrow{i} X$ is a cofibration, and $A \xrightarrow{f} Z$ is any map. We claim that $Z \hookrightarrow Z \cup_A X$ is a cofibration. Consider the diagram

$$\begin{array}{ccccc} A & \xrightarrow{f} & Z & \xrightarrow{h} & Y^I \\ \downarrow i & \nearrow \tilde{h} & \downarrow & & \downarrow \text{ev}_0 \\ X & \xrightarrow{\quad} & Z \cup_A X & \longrightarrow & Y \end{array}$$

and note that \tilde{h} exists by the HEP for i and $h \circ f$. We therefore have that $Z \cup_A X \rightarrow Y^I$ exists via the universal property of the pushout.

For (3), suppose $i: A \rightarrow X$ is a retract of $j: B \rightarrow Z$, that is, we have a diagram

$$\begin{array}{ccccc} A & \longrightarrow & B & \longrightarrow & A \\ \downarrow i & & \downarrow j & & \downarrow i \\ X & \longrightarrow & Z & \longrightarrow & X \end{array}$$

we sack a test diagram to it:

$$\begin{array}{ccccccc} A & \longrightarrow & B & \longrightarrow & A & \xrightarrow{\quad} & Y^I \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \text{ev}_0 \\ X & \longrightarrow & Z & \xrightarrow{\quad} & X & \longrightarrow & Y \end{array}$$

If j is a cofibration, then a lift $\tilde{h}: X \rightarrow Y^I$ exists, and composing with $X \rightarrow Z$, we get that i is a cofibration.

(4) and (5) are left as an exercise.

□

Corollary 4.5. If $A \xhookrightarrow{i} X$ is a relative CW complex, then i is a cofibration.

Proof. We know that $S^{n-1} \hookrightarrow D^n$ is a cofibration. Using (2), (4) it follows that the inclusion of skeleta at each stage is a cofibration. Lastly we use (5), since $X = \text{colim}_n X_n$ is a sequential colimit. □

Proposition 4.6. If $i: A \hookrightarrow X$ is a cofibration, and Z is any space, then

$$i \times \text{id}_Z: A \times Z \rightarrow X \times Z$$

is also a cofibration.

Proof. Take a test diagram of the form

$$\begin{array}{ccc} A & \longrightarrow & Y^I \\ i \downarrow & & \downarrow \\ X & \longrightarrow & Y \end{array}$$

which, by adjunction, corresponds to a diagram, which can be filled, since i is a cofibration

$$\begin{array}{ccc} A & \longrightarrow & (Y^Z)^I \\ i \downarrow & \nearrow & \downarrow \\ X & \longrightarrow & Y^Z. \end{array}$$

□

A More category theory: properties of morphisms

As we have seen, limits and colimits allow us ways to construct new objects, morphisms, and universal properties, over indexing diagrams. In particular we might be interested in relating certain properties of morphisms in a category to induced morphisms produced out of a colimit. As a motivating example, consider the following question.

Question A.1. Let I be a small indexing diagram, and let $\alpha, \beta : I \rightarrow \text{Set}$ denote two functors, and let $A_i := \alpha(i)$ and $B_i = \beta(i)$ denote the sets at each object $i \in I$. Suppose we have a natural transformation between these functors, consisting of functions $f_i : A_i \rightarrow B_i$ for each i . If each f_i is injective, is it true that the induced map $f : \text{colim } \alpha \rightarrow \text{colim } \beta$ is injective as well?

It turns out the answer to this diagram depends on the shape of I . It is true if the colimits are *filtered*, which is a condition on the indexing diagram which tells us that it interacts well with finite limits. This motivates the more broad question of what properties of morphisms are preserved under limits and colimits. In general this is a hard question, but it will be important when we investigate fibrations and cofibrations in the category of topological spaces.

A.1 Stability and closure definitions

Let \mathcal{C} be a category, not necessarily assumed to be locally small. We start with an easy definition.

Definition A.2. Let \mathbf{P} be a property of morphisms in \mathcal{C} . We say that \mathbf{P} is *closed under composition* if, anytime we have two composable morphisms $f : x \rightarrow y$ and $g : y \rightarrow z$, if both f and g have property \mathbf{P} , then the composite $g \circ f$ does as well.

Definition A.3. Let \mathbf{P} be a property of morphisms in \mathcal{C} . We say that \mathbf{P} *satisfies 2-out-of-3* if for every commutative diagram of the form

$$\begin{array}{ccc} A & \xrightarrow{f} & B \\ & \searrow g \circ f & \downarrow g \\ & & C, \end{array}$$

if any two of f , g , or $g \circ f$ have property \mathbf{P} , then the third does as well.

Exercise A.4.

1. Prove that isomorphisms satisfy 2-out-of-3.
2. In the category Set , prove that injections and surjections do not satisfy 2-out-of-3.

Definition A.5. Let \mathbf{P} be a property of morphisms.

1. We say that \mathbf{P} is a *left cancellative property* if any time $g \circ f$ has property \mathbf{P} , this implies that f has property \mathbf{P} as well.

2. We say that \mathbf{P} is a *right cancellative property* if any time $g \circ f$ has property \mathbf{P} , this implies that g has property \mathbf{P} as well.

As a warning to the reader, the terminology in ?? is not standard, although we would advocate for its usage. The notion of left cancellative properties is referred to as (CANC) in [?, Appendix C], and has many examples in algebraic geometry (e.g. immersions, locally of finite type, purely inseparable, quasi-separated, separated). Many other examples occur under hypotheses on g , e.g. if it is separated or unramified. In a broader categorical context, we will see that mono-(resp. epi-)morphisms are left (resp. right) cancellative.

Definition A.6. Let \mathbf{P} be a property of morphisms. We say that \mathbf{P} is *closed under retracts* if, for any $f : A \rightarrow B$ with property \mathbf{P} , and any $g : X \rightarrow Y$ fitting into a commutative diagram

$$\begin{array}{ccccc} & & \text{id}_X & & \\ & \swarrow & & \searrow & \\ X & \xrightarrow{\quad} & A & \xrightarrow{\quad} & X \\ g \downarrow & & \downarrow f & & \downarrow g \\ Y & \xrightarrow{\quad} & B & \xrightarrow{\quad} & Y, \\ & \searrow & & \swarrow & \\ & & \text{id}_Y & & \end{array}$$

we have that g has property \mathbf{P} as well.

Definition A.7. Let \mathbf{P} be a property of morphisms. Then we say that \mathbf{P} is *stable under pullback* (often also called *stable under base change*) if for any pullback diagram of the form

$$\begin{array}{ccc} C & \xrightarrow{j} & D \\ k \downarrow \lrcorner & & \downarrow f \\ A & \xrightarrow{g} & B, \end{array}$$

if f has property \mathbf{P} , then k has property \mathbf{P} as well. Dually, we say that \mathbf{P} is *stable under pushout* if for any pushout diagram of the form

$$\begin{array}{ccc} C & \xrightarrow{j} & D \\ k \downarrow \lrcorner & \lrcorner & \downarrow f \\ A & \xrightarrow{g} & B, \end{array}$$

if k has property \mathbf{P} , then f has property \mathbf{P} as well.

Exercise A.8.

1. Prove that isomorphisms are always stable under pushout and pullback.
2. Prove in the category **Set** that injective functions are stable under pullback, and surjective functions are stable under pushout.

Thus far we have discussed closure properties internal to a category. We might wonder how properties translate across functors.

Definition A.9. Let $F : \mathcal{C} \rightarrow \mathcal{D}$ be a functor, and let \mathbf{P} be a property of morphisms.

1. We say that F preserves property \mathbf{P} if any time $f : x \rightarrow y$ is a morphism in \mathcal{C} with property \mathbf{P} , we have that $Ff : Fx \rightarrow Fy$ has property \mathbf{P} as well.
2. We say that F reflects property \mathbf{P} if any tie $f : x \rightarrow y$ is a morphism in \mathcal{C} , if $Ff : Fx \rightarrow Fy$ has property \mathbf{P} , then f must necessarily have property \mathbf{P} as well.

Remark A.10. We have that F always preserves isomorphisms (this is part of the property of being a functor). It is *not true* that F needs to reflect isomorphisms. For example if X is a topological space with a non-trivial topology, then the map $\text{id} : X \rightarrow X_{\text{disc}}$ from X to itself with the discrete topology is not a homeomorphism, however its underlying set map is a bijection. (That is, the forgetful functor $\text{Top} \rightarrow \text{Set}$ does not reflect isomorphisms).

Exercise A.11. If F is full and faithful, it reflects isomorphisms.

A.2 Monomorphisms and epimorphisms

?? generalizes, as the notions of being injective and surjective in Set are equivalent to more abstract categorical conditions. We begin by generalizing injections.

Definition A.12. Let \mathcal{C} be a category. Then a morphism $f : x \rightarrow y$ is a *monomorphism* if any of the following equivalent conditions hold:

1. For any pair of morphisms $g, h : z \rightarrow x$ so that $f \circ g = f \circ h$, that is:

$$z \rightrightarrows x \rightarrow y,$$

we have that $g = h$. (Another way of phrasing this is that f is *left cancellable*).

2. The following diagram is a pullback:

$$\begin{array}{ccc} x & \xrightarrow{\text{id}_x} & x \\ \downarrow \text{id}_x & \lrcorner & \downarrow f \\ x & \xrightarrow{f} & y. \end{array}$$

If \mathcal{C} is locally small, there is another equivalent condition:

3. The induced functor $\text{Hom}_{\mathcal{C}}(-, x) \xrightarrow{f \circ -} \text{Hom}_{\mathcal{C}}(-, y)$ is a natural injection, meaning that $\text{Hom}_{\mathcal{C}}(z, x) \xrightarrow{f \circ -} \text{Hom}_{\mathcal{C}}(z, y)$ is an injective function for any $z \in \mathcal{C}$.

Exercise A.13. Prove that the definitions in ?? are equivalent.

Example A.14. We have that isomorphisms and equalizers are always monomorphisms. Any morphism from a terminal object is a monomorphism.

Exercise A.15. (*Closure properties of monomorphisms*)

1. Monomorphisms are closed under composition
2. Monomorphisms are stable under pullback
3. Monomorphisms are left cancellative.

Exercise A.16. (*Left adjoints preserve monomorphisms*) Let $F : \mathcal{C} \rightleftarrows \mathcal{D} : G$ be an adjunction between locally small categories. Then if $f : x \rightarrow y$ is a monomorphism in \mathcal{C} , we have that $Ff : Fx \rightarrow Fy$ is a monomorphism in \mathcal{D} . (Hint: use the natural bijection associated to the adjunction, together with ??, Definition (iii)).

There is a dual notion, called an *epimorphism*.

Definition A.17. Let \mathcal{C} be a category. Then a morphism $f : x \rightarrow y$ is a *epimorphism* if any of the following equivalent conditions hold:

1. For any pair of morphisms $g, h : y \rightarrow z$ so that $g \circ f = h \circ f$, that is:

$$x \rightarrow y \rightrightarrows z,$$

we have that $g = h$. (Another way of phrasing this is that f is *right cancellable*).

2. The following diagram is a pushout:

$$\begin{array}{ccc} x & \xrightarrow{f} & y \\ f \downarrow & \lrcorner & \downarrow \text{id}_y \\ y & \xrightarrow{\text{id}_y} & y. \end{array}$$

If \mathcal{C} is locally small, there is another equivalent condition:

3. The induced functor $\text{Hom}_{\mathcal{C}}(y, -) \xrightarrow{- \circ f} \text{Hom}_{\mathcal{C}}(x, -)$ is a natural injection, meaning that $\text{Hom}_{\mathcal{C}}(y, z) \xrightarrow{- \circ f} \text{Hom}_{\mathcal{C}}(x, z)$ is an injective function for any $z \in \mathcal{C}$.

Epimorphisms satisfy all the dual properties to monomorphisms.

Exercise A.18. (*Properties of epimorphisms*)

1. Every isomorphism is an epimorphism, as is every coequalizer.
2. Any morphism to an initial object is an epimorphism.

3. Epimorphisms are closed under composition.
4. Epimorphisms are stable under pushout.
5. Epimorphisms are right cancellative.
6. Right adjoints preserve epimorphisms.

As we have hinted at, monomorphisms and epimorphisms generalize the notions of injectivity and surjectivity in \mathbf{Set} . We can ask then whether categories which we think of as “sets with extra data” have the property that their monomorphisms are just those underlain by injections. Phrased differently, does the forgetful functor $U : \mathcal{C} \rightarrow \mathbf{Set}$ reflect mono and epimorphisms? This turns out to be true in some generality, but we must first make rigorous what it means to be a “set with extra structure.”

Definition A.19. A *concrete category* is a locally small category \mathcal{C} , together with faithful functor to sets $U : \mathcal{C} \rightarrow \mathbf{Set}$. We think of this functor as “forgetting” the data.

Examples A.20. The following categories are concrete: \mathbf{Grp} , \mathbf{Poset} , \mathbf{Vect} , \mathbf{Top} , .

[add more](#)

Proposition A.21. Any faithful functor reflects monomorphisms and epimorphisms.

Thus we see that all the categories in ?? have the property that their monomorphisms are underlying injections, and epimorphisms are underlying surjections. We summarize this in the following table.

Table 2: Examples of monomorphisms and epimorphisms

Category	Monomorphisms	Epimorphisms
\mathbf{Set}	injections	surjections
\mathbf{Grp}	underlying injections	underlying surjections

Counterexample A.22. We have that the inclusion $\mathbb{Z} \hookrightarrow \mathbb{Q}$ is an epimorphism in the category \mathbf{Ring} of unital rings. This tells us that the forgetful functor $U : \mathbf{Ring} \rightarrow \mathbf{Set}$ is *not* faithful.

A.3 Properties of morphisms can induce properties of objects

Suppose we have a commutative diagram of the form

$$\begin{array}{ccc} A & \xrightarrow{i} & B \\ & \searrow \text{id}_A & \downarrow r \\ & & A. \end{array}$$

In this case we say the object A is a *retract* of B . We can ask about what properties of objects descend to their retracts, motivating the following definition.

Definition A.23. Let \mathbf{O} be a property of objects in \mathcal{C} (we can just think of this as some subclass of the class of objects). Then we say that \mathbf{O} is *closed under retracts* if, any time $B \in \mathbf{O}$, and A is a retract of B , we have that $A \in \mathbf{O}$ as well.

We can ask about how a property of objects could potentially be related to a property of morphisms. In particular, we could ask about how properties of morphisms might induce properties of objects. Our perspective on this is stolen from algebraic geometry, in which a scheme is defined to have a property if and only if its structure morphism has the associated property. In the world of schemes and varieties, there basically don't exist properties for objects, only properties for morphisms. This is a feature of life with a terminal object. In many situations, such as topological spaces, we have the same luxury.

Terminology A.24. Let \mathcal{C} be a category with a terminal object $*$, and let \mathbf{P} be a property of morphisms in \mathcal{C} . Then we have an *induced property of objects* \mathbf{O} , defined by saying that $X \in \mathbf{O}$ if the unique morphism $X \xrightarrow{!} *$ lies in \mathbf{P} .

Exercise A.25. Let \mathcal{C} be a category with a terminal object. Prove that if \mathbf{P} is a property of morphisms closed under retracts in the sense of ??, then the induced property of objects is closed under retracts in the sense of ??.

Remark A.26. The passage from fibrations to fibrant objects follows ??.

A.4 Preservation properties under limits and colimits

Definition A.27. Let I be an indexing category, let \mathcal{C} be a category, and let \mathbf{P} be a property of morphisms in \mathcal{C} . Let $f_1, f_2 : I \rightarrow \mathcal{C}$ be two diagrams in \mathcal{C} , and let $\eta : f_1 \Rightarrow f_2$ be a natural transformation between them. We say that η has property \mathbf{P} *levelwise* (or has property \mathbf{P} *naturally*) if each of the components $\eta_c : f_1(c) \rightarrow f_2(c)$ has property \mathbf{P} . As some examples:

1. a *natural isomorphism* is a natural transformation whose components are isomorphisms.
2. a *natural monomorphism* is a natural transformation whose components are monomorphisms.

Definition A.28. Let I be an indexing category, and let \mathbf{P} be a property of morphisms in \mathcal{C} . We say that \mathbf{P} is *preserved under I -shaped colimits* if, any time we have a natural transformation $\eta : f_1 \Rightarrow f_2$ which has property \mathbf{P} levelwise, we have that the induced map

$$\operatorname{colim}_I(f_1) \rightarrow \operatorname{colim}_I(f_2)$$

is in \mathbf{P} as well (assuming both colimits exist). Dually we have a notion of preservation under I -shaped limits.

Example A.29. We have that isomorphisms are preserved under arbitrary limits and colimits.

Example A.30. If $I = \bullet \bullet$ is a discrete category on two points, we say that a property \mathbf{P} is *preserved under products* (resp. *coproducts*) if it is preserved under I -shaped limits (resp. colimits).

Proposition A.31. We have that

1. Monomorphisms are preserved under products
2. Epimorphisms are preserved under coproducts.

Proof. We will prove (1) and remark that (2) follows formally. Let $f : A \rightarrow B$ and $g : C \rightarrow D$ be monomorphisms. Then assuming their products exist, there is an induced map $(f \times g) : A \times C \rightarrow B \times D$. We claim that this is a monomorphism as well. Via ??, we can restate the statement that f and g are monomorphisms into the statement that these diagrams are pullbacks

$$\begin{array}{ccc} A & \longrightarrow & A \\ \downarrow \lrcorner & & \downarrow \\ A & \longrightarrow & B \end{array} \quad \begin{array}{ccc} C & \longrightarrow & C \\ \downarrow \lrcorner & & \downarrow \\ C & \longrightarrow & D. \end{array}$$

Since limits commute, we have that taking a product of the two pullbacks is the same as the pullback of the product of the two diagrams, that is, the following diagram is a pullback

$$\begin{array}{ccc} A \times C & \xrightarrow{\text{id} \times \text{id}} & A \times C \\ \text{id} \times \text{id} \downarrow \lrcorner & & \downarrow f \times g \\ A \times C & \xrightarrow{f \times g} & B \times D. \end{array}$$

Thus $f \times g$ is a monomorphism. □

This is an instance of a more general phenomenon, namely functors preserving limits and colimits.

Definition A.32. Let $F : \mathcal{C} \rightarrow \mathcal{D}$ be a functor, and let I be an indexing diagram.

1. We say that F *preserves* I -shaped limits if, for any functor $j : I \rightarrow \mathcal{C}$, we have that the natural map is an isomorphism

$$F(\lim(j)) \cong \lim(F \circ j).$$

That is, a limit cone over j is sent to a limit cone over $F \circ j$.

2. We say that F *reflects* I -shaped limits if, for any functor $j : I \rightarrow \mathcal{C}$, if we have that $F(c)$ is the limit of $F \circ j$, then c is a limit of j . Phrased differently, a limit cone over $F \circ j$ in the image of F must have come from a limit cone over j .
3. We say F *creates* limits if it preserves and reflects them.

We have analogous definitions for colimits.

This relates to some things we have already seen: e.g. ?? said that left adjoints preserve colimits, and right adjoints preserve limits.

Proposition A.33. Hom functors preserve limits in both arguments. That is, if \mathcal{C} is a locally small category, then the bifunctor

$$\text{Hom} : \mathcal{C}^{\text{op}} \times \mathcal{C} \rightarrow \text{Set}$$

preserves limits in both arguments (limits in \mathcal{C}^{op} are colimits in \mathcal{C}).

Corollary A.34. Let \mathcal{C} be locally small. Then the Yoneda embedding $y : \mathcal{C} \hookrightarrow \text{Fun}(\mathcal{C}^{\text{op}}, \text{Set})$ preserves and reflects all limits.

Proposition A.35. A fully faithful functor reflects all limits and colimits.

Remark A.36. If F is a functor preserving all limits over the diagram $I = \bullet \rightarrow \bullet \leftarrow \bullet$, we say that it *preserves pullbacks*. Dually if F preserves limits over the span diagram $J = \bullet \leftarrow \bullet \rightarrow \bullet$, we say it is *preserves pushouts*.

Exercise A.37. Let $F : \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. If F preserves pullbacks, then it preserves monomorphisms.
2. If F preserves pushouts, then it preserves epimorphisms.

Thus far we have defined two notions of preservation of properties. Namely, properties preserved under functors (as in ??), and properties preserved under limits and colimits (as in ??). We can see that these are both instances of the same idea.

A.5 Colimits and limits as functors

In order to relate these two notions of preservation, we should relate one to the other. In particular we claim that the most general notion of preservation of properties of morphisms is under a functor. In order to see that this encapsulates the other definition, we should view the construction of limits and colimits as a functor in some sense.

Let \mathcal{C} be a category, and I be an indexing category which we want to take limits and colimits over. Then there is a *diagonal functor*

$$\Delta : \mathcal{C} \rightarrow \text{Fun}(I, \mathcal{C}).$$

This sends an object c to the functor $\Delta_c : I \rightarrow \mathcal{C}$, where $\Delta_c(i) = c$ for all $i \in I$, and $\Delta_c(i \rightarrow i') = \text{id}_c$. That is, Δ_c is really a constant functor at the object $c \in \mathcal{C}$. For a morphism $f : c \rightarrow c'$, we have an induced natural transformation $\Delta_c \Rightarrow \Delta_{c'}$, all of whose components are f .

[[todo]]

A.6 Filtered limits and colimits

[[todo]]

B Unsorted subsections on category theory

B.1 Conventions

We record some standard notation for use in these notes.

Notation B.1. We denote an *initial object* in a category \mathcal{C} by \emptyset . We denote a *terminal object* in a category \mathcal{C} by $*$. If $X \in \mathcal{C}$ is arbitrary, it receives a unique map from the initial object and to the terminal object. We decorate each of these with shriek:

$$\begin{aligned} \emptyset &\xrightarrow{!} X \\ X &\xrightarrow{!} *. \end{aligned}$$

Notation B.2. Let \mathcal{C} be a category, and let $X \in \mathcal{C}$ be an arbitrary object. If the product $X \times X$ exists, there is a *diagonal map*, which we denote by

$$X \xrightarrow{\Delta} X \times X,$$

defined to be the unique map provided to us by the universal property of the product

$$\begin{array}{ccccc} & & X & & \\ & \swarrow id_X & \downarrow \Delta & \searrow id_X & \\ & X \times X & & & \\ \swarrow id_X & & \searrow pr_1 & & \searrow id_X \\ X & & & & X. \\ & \searrow pr_2 & & & \end{array}$$

Notation B.3. Let \mathcal{C} be a category, and let $X \in \mathcal{C}$ be an arbitrary object. If the coproduct $X \amalg X$, there is a *fold map*, which we denote by

$$X \amalg X \xrightarrow{\nabla} X,$$

defined to be the unique map provided to us by the universal property of the coproduct

$$\begin{array}{ccccc} & & X & & \\ & \swarrow i_1 & & \searrow i_2 & \\ & X \amalg X & & & \\ \swarrow id_X & & \downarrow \nabla & & \searrow id_X \\ X & & & & X. \\ & \searrow & & & \end{array}$$

The terminology for the *diagonal* map comes from the world of sets (or concrete categories more generally), where the function $\Delta : X \rightarrow X \times X$ is defined elementwise by $x \mapsto (x, x)$. That is, its image is the diagonal in the product. The *fold* map comes from the mental image of taking two disjoint copies of X and folding them over one another into one copy of X .

Notation B.4. Let \mathcal{C} be a category with products, and let $f : A \rightarrow B$ and $g : C \rightarrow D$ be two morphisms. Then we denote by

$$f \times g : A \times C \rightarrow B \times D$$

the morphism given via the universal property

$$\begin{array}{ccccc} & & A \times B & & \\ & \swarrow & \downarrow f \times g & \searrow & \\ A & & C \times D & & B \\ \downarrow f & \swarrow & \searrow & \downarrow g & \\ C & & & & D. \end{array}$$

Similarly if \mathcal{C} is a category with coproducts, we denote by

$$f \amalg g : A \amalg C \rightarrow B \amalg D$$

the morphism provided by the universal property

$$\begin{array}{ccccc} A & & & & B \\ \downarrow f & \searrow & & \swarrow & \downarrow g \\ C & & A \amalg B & & D \\ \searrow & \downarrow f \amalg g & \swarrow & & \\ & & C \amalg D. & & \end{array}$$

B.2 Laws for pullbacks and pushouts

Frequently we will be asked to glue together commutative squares and talk about whether the composite square is a pullback and/or whether the individual squares are pullbacks. This is discussed in the so-called *pasting law*.

Proposition B.5. (*Pasting law for pullbacks and pushouts*) Let \mathcal{C} be an arbitrary category, and consider a commutative diagram of the following form

$$\begin{array}{ccccc} \bullet & \longrightarrow & \bullet & \longrightarrow & \bullet \\ \downarrow & & \downarrow & & \downarrow \\ \bullet & \longrightarrow & \bullet & \longrightarrow & \bullet. \end{array}$$

1. If the right square is a pullback, then the total square is a pullback if and only if the left square is a pullback.
2. If the left square is a pushout, then the total square is a pushout if and only if the right square is a pushout.

We also have the “magic square,” which is generally stated for varieties or schemes, but holds in a more broad context.

Proposition B.6. (*Magic pullback square*) Let \mathcal{C} be a locally small category with products and pullbacks. Let $f : X \rightarrow Z$, and $g : Y \rightarrow Z$ be morphisms in \mathcal{C} . Then the following square is a pullback

$$\begin{array}{ccc} X \times_Y Z & \longrightarrow & X \times Y \\ \downarrow & \lrcorner & \downarrow f \times g \\ Z & \xrightarrow{\Delta} & Z \times Z. \end{array}$$

Proof. We first check that this holds if $\mathcal{C} = \mathbf{Set}$. This is certainly true, since elements of $(X \times Y) \times_{Z \times Z} Z$ are precisely elements $(x, y) \in X \times Y$ so that $f(x) = g(y)$. Then for any locally small category \mathcal{C} , we have that this diagram is a levelwise pullback in $\text{Fun}(\mathcal{C}^{\text{op}}, \mathbf{Set})$. Finally we remark that under the Yoneda embedding $y : \mathcal{C} \hookrightarrow \text{Fun}(\mathcal{C}^{\text{op}}, \mathbf{Set})$, limits are reflected. \square

The magic pullback square is generally stated in the following form.

Corollary B.7. Let \mathcal{C} be a locally small category, and $S \in \mathcal{C}$ be any element. Then if $f : X \rightarrow Z$ and $g : Y \rightarrow Z$ are morphisms over S , we have a pullback square

$$\begin{array}{ccc} X \times_Y Z & \longrightarrow & X \times_S Y \\ \downarrow & \lrcorner & \downarrow f \times g \\ Z & \xrightarrow{\Delta} & Z \times_S Z. \end{array}$$

C Homotopy colimits

Here we explore instances in which homotopy (co)limits appear in the basic curriculum of algebraic topology, namely in [?] and [?]. A rigorous treatment of homotopy colimits is not provided here, we defer to the far better expositors Dugger and Riehl for their expositions of simplicial and categorical understandings of homotopy colimits [?, ?]. We would posit that homotopy colimits are an intuitive concept to grasp and work with, and that recognizing them as they occur in basic algebraic topology provides the reader with another tool to grasp the material.

C.1 Intro to homotopy colimits

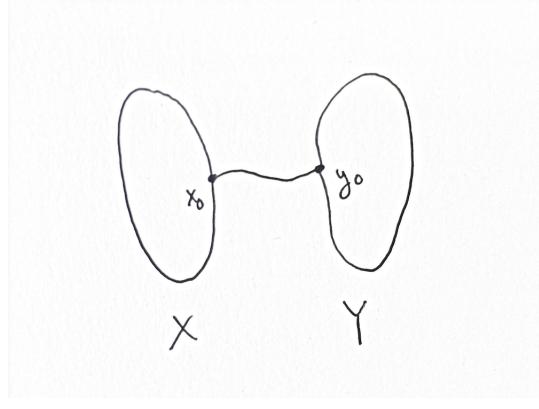
As described above, we neglect to provide a rigorous definition of homotopy colimits, as the rigorous definitions (hocolim is the derived functor of colim; homotopy colimits are the geometric realization of the simplicial replacement) are technical to state. Instead, we provide the following characterization of homotopy colimits, based on an intuitive understanding of colimits:

Colimits are obtained by gluing spaces.

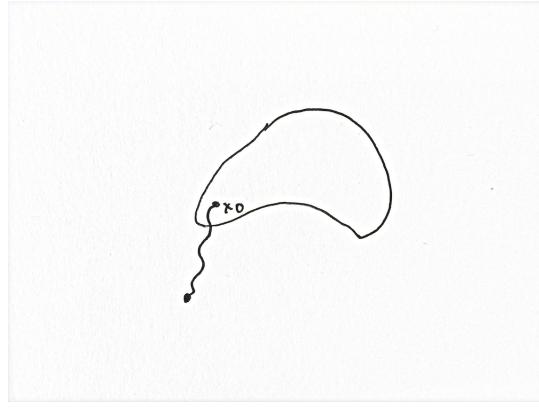
Homotopy colimits are obtained by gluing spaces *with wiggle room, in a continuous fashion*.

What do we mean by this? Say we want to glue two spaces X and Y together along distinguished basepoints to form a wedge product $X \vee Y$. How do we do this in general? We take the disjoint union $X \amalg Y$ and mod out by the equivalence relation $x_0 \sim y_0$. Phrased differently, we glue x_0 and y_0 together to force them to become the same point in the quotient space.

Instead of gluing them directly together, we could instead draw a path connecting x_0 and y_0 . Now instead of formally identifying the two points, we provide them a path by which one can travel to the other.



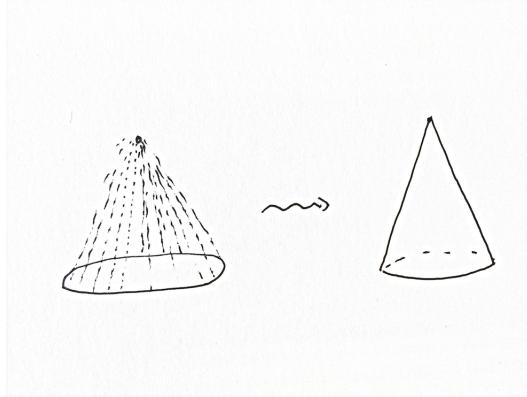
Example C.1. As another example, suppose $* \hookrightarrow X$ is the inclusion of a point $x \in X$. Taking the cofiber of this map⁵ is the same as simply gluing the point $*$ to $x \in X$, and you simply end up with the space X . If, instead, you wanted to take the *homotopy cofiber* of this map, you would end up with the space X , with a small whisker protruding from the point x , ending at the point $*$. This procedure has a name, and it is actually called *whiskering*. For example if (X, x) is a based space which is not well based⁶, we can take the based space $(\text{hocolim}(* \hookrightarrow X), *)$, which becomes well-based.



⁵Recall the cofiber of a map $f : X \rightarrow Y$ is the colimit $\text{colim} (* \leftarrow X \xrightarrow{f} Y)$.

⁶Recall a space is *well-based/non-degenerately based* if the inclusion of the basepoint is a cofibration.

Example C.2. Consider the map $S^1 \rightarrow *$ collapsing the sphere to a point. The cofiber of this map is $*$, that is, a one-point space. However to form the homotopy cofiber, we must draw a path from each point on S^1 to the point $*$. Here is where we sweep some more rigor under the rug, and illustrate what we mean by “in a continuous fashion” in our characterization of homotopy colimits. When creating our paths from points on S^1 to $*$, a small change in the choice of point on the circle S^1 should correspond to a small change in the path drawn. We shouldn’t think of these paths as a loose collection of uncountably many strings, flying everywhere and connecting each point on S^1 to $*$. Instead, nearby strings should coagulate to form surfaces.



If you’ve followed this rough description, then it would make sense to you that the homotopy cofiber of the map $S^1 \rightarrow *$ becomes a hollow cone over S^1 , whose vertex is the point $*$. If, on the other hand, this lack of rigor has disgusted you, then the authors understand wholeheartedly and invite you to read [?].

In the previous examples, the resulting space obtained by taking a homotopy colimit was weakly homotopy equivalent to the original one obtained by taking a colimit. We can ask whether this will always be the case, which the following example (a rephrased version of Example 2.1 in [?]) illustrates.

Example C.3. Consider the diagram $* \leftarrow S^1 \rightarrow *$. Its colimit is the pushout $* \amalg_{S^1} * \cong *$, which is just a one-point space. On the other hand, its homotopy colimit can be constructed via the previous example. By gluing S^1 to each point $*$, we obtain two hollow cones which are identified together along their bases. That is, we obtain a 2-sphere S^2 . Note that $S^2 \not\simeq *$!

This is an example of a general phenomena; for a diagram $D : I \rightarrow \text{Top}$, it is often the case that $\text{colim}(D) \not\simeq \text{hocolim}(D)$.

Remark C.4. In the previous section we have said that a homotopy colimit “is” a certain space. The reader should be advised that homotopy colimits are only defined up to weak equivalence. This turns out to be both a blessing and a curse, in that we fail to obtain a well-defined construction in the topological category, however the ambiguity allows homotopy colimits to satisfy a property that colimits fail to satisfy: *homotopy invariance*. We will make this precise.

C.2 Homotopy Invariance

Definition C.5. A *weak homotopy equivalence of diagrams* is a natural transformation $D \Rightarrow D'$ (occasionally denoted $D \simeq D'$) between two diagrams $D, D' : I \rightarrow \text{Top}$ whose components are weak homotopy equivalences.

Example C.6. Let our index category be $I = \bullet \leftarrow \bullet \rightarrow \bullet$, and let $D(I) = (D^{n+1} \hookrightarrow S^n \hookrightarrow D^{n+1})$, and $D'(I) = (* \leftarrow S^n \rightarrow *)$. Then there is a weak homotopy equivalence of diagrams $D \Rightarrow D'$ whose components are the identity map on S^n and the contraction $D^{n+1} \xrightarrow{\sim} *$ on the disks.

Remark C.7. Colimits fail to satisfy *homotopy invariance*. That is, for a weak homotopy equivalence of diagrams $D \simeq D'$, we may have that $\text{colim}(D) \not\simeq \text{colim}(D')$.

Exercise C.8. See in Example ?? that $\text{colim}(D) = S^{n+1}$ but $\text{colim}(D') = *$.

Theorem C.9. Homotopy colimits satisfy homotopy invariance. That is, for $D \simeq D'$, one always has that

$$\text{hocolim}(D) \simeq \text{hocolim}(D').$$

Corollary C.10. Given any diagram, we may replace maps and objects in the diagram by weakly equivalent ones and obtain the same homotopy colimit.

C.3 Homotopy colimits coinciding with colimits

There are many deep questions to ask about homotopy colimits, but perhaps the first one that we might be curious about is when homotopy colimits and colimits coincide. This question is non-trivial to answer, and as always we defer to [?] for a full treatment. However we will give one example, which is a stronger condition on a diagram than one needs in general, but will suit our examples:

Proposition C.11. If a diagram $D : I \rightarrow \text{Top}$ has the property that all of its maps are cofibrations, then $\text{colim}(D) \simeq \text{hocolim}(D)$.

In particular, if the maps are inclusions of subspaces which form a relative CW complex, they are cofibrations.

This fact, combined with homotopy invariance of homotopy colimits, will allow us to provide a characterization of a lot of phenomena occurring in algebraic topology in terms of homotopy colimits.

Example C.12. We have that $\Sigma X = \text{hocolim}(* \leftarrow X \rightarrow *)$.

Proof. Let CX denote the cone over X , and note that $CX \simeq *$ is contractible. Then since the

inclusion $X \hookrightarrow CX$ is a relative CW complex, one has

$$\begin{aligned} \Sigma X &= \text{colim} \left(\begin{array}{c} X \hookrightarrow CX \\ \downarrow \\ CX \end{array} \right) = \text{hocolim} \left(\begin{array}{c} X \hookrightarrow CX \\ \downarrow \\ CX \end{array} \right) \\ &= \text{hocolim} \left(\begin{array}{c} X \hookrightarrow * \\ \downarrow \\ * \end{array} \right). \end{aligned}$$

□

Example C.13. Let $\varphi : S^n \rightarrow X_n$ be the attaching map for an $(n+1)$ -cell, and let X_{n+1} be the space obtained by attaching this cell. Then

$$X_{n+1} = \text{hocofib} \left(S^n \xrightarrow{\varphi} X_n \right).$$

Proof. Again we apply the previous proposition and homotopy invariance of homotopy colimits. We have that

$$\begin{aligned} X_{n+1} &= \text{colim} \left(\begin{array}{c} S^n \hookrightarrow X_n \\ \downarrow \\ D^{n+1} \end{array} \right) = \text{hocolim} \left(\begin{array}{c} S^n \hookrightarrow X_n \\ \downarrow \\ D^{n+1} \end{array} \right) \\ &= \text{hocolim} \left(\begin{array}{c} S^n \hookrightarrow X_n \\ \downarrow \\ * \end{array} \right) = \text{hocofib}(\varphi). \end{aligned}$$

□

Example C.14. For a map $f : X \rightarrow Y$, the *mapping cylinder*, defined on [?, p.2] may be thought of as $M_f = \text{hocolim}(X \xrightarrow{f} Y)$.

Example C.15. For a map $f : X \rightarrow Y$ *mapping cone* C_f , defined on [?, p.13], is the homotopy cofiber of the map f :

$$C_f = \text{hocofib}(f).$$

Example C.16. The *join* of two spaces X and Y , defined on [?, p.9], is the homotopy pushout $\text{hocolim}(X \leftarrow X \times Y \rightarrow Y)$.

Example C.17. As a generalization of the previous example, the *double mapping cylinder*, defined on [?, p.80], is the homotopy pushout $\text{hocolim}(A \leftarrow X \rightarrow B)$.

Example C.18. The *mapping telescope*, defined on [?, p.138], is the homotopy colimit

$$\text{hocolim} \left(X_0 \xrightarrow{f_0} X_1 \xrightarrow{f_1} \cdots \right).$$

Theorem C.19. [?, Theorem 24.9] Homotopy colimits commute.

Corollary C.20. On [?, p.57], a critical aspect of the cofiber sequence generated by a map f is that there is a weak equivalence (really a homeomorphism) $\Sigma C_f \simeq C(\Sigma f)$. This can be easily remembered by the fact that homotopy colimits commute.

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